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Dissertation

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Semantic visualization for smart spaces – merging the material and digital worlds

Ilkka Niskanen

VTT

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Semantic visualization for smart spaces – merging the material and digital worlds

Ilkka Niskanen

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Preface

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Oulu, 27th April 2015

Ilkka Niskanen

Academic dissertation

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List of publications

This thesis is based on the following original publications, which are referred to in the text as I–V. The publications are reproduced with kind permission from the publishers.

I Niskanen, I., Kalaoja, J., Kantorovitch, J., & Piirainen, T. (2007). An interactive ontology visualization approach for the networked home environment. *International journal of computer and information science and engineering*, *1*(2), pp. 102–107.

II Kantorovitch, J., Kalaoja, J., Niskanen, I., & Piirainen, T. (2008). Towards a better understanding of semantic ontology-based home service modelling. In *Advanced Information Networking and Applications, 2008. AINA 2008. 22nd International Conference on* (pp. 26–31). IEEE.

III Niskanen, I., & Kantorovitch, J. (2010). Ontology driven data mining and information visualization for the networked home. In *Research Challenges in Information Science (RCIS), 2010 Fourth International Conference on* (pp. 147–156). IEEE.

IV Niskanen, I., Kantorovitch, J., & Golenzer, J. (2012). Monitoring and Visualisation Approach for Collaboration Production Line Environments: A Case Study in Aircraft Assembly. *International Journal on Human Computer Interaction*, 3(2), pp. 35–50.

V Niskanen, I., Purhonen, A., Kuusijärvi, J., & Halmetoja, E., (2014) Towards Semantic Facility Data Management. In *The Third International Conference on Intelligent Systems and Applications (pp. 85-90).*

Contents

1. Introduction

Computers have a tremendous impact on modern society. People in different countries are now able to communicate in real time and meet other people without leaving their homes. Computer technology has become an integral part of society and affects every area of our lives, whether it is recreational or work related. Modern technological means are sensitive and responsive to people and their behaviours, delivering advanced and personalized services. Although the purpose of technological development is to improve the welfare of people and the environment, it also poses new challenges in terms of privacy, data protection, and ethics.

Constructed facilities are inherently long-term investments that require large capital expenditure. In recent years, the construction industry has had to respond to emerging requirements imposed by the vast technological developments. Processes of production, from the generation of new products to the construction and implementation of infrastructure and urban equipment, are ever demanding, as they require more efficient technologies, both technically and environmentally (Hernández-Moreno 2009). Additionally, more attention has been given to the impact of the overall qualitative aspects of environments on users' perceived satisfaction and ability to work (Leifer 1998).

The recent technological advances have enabled new types of services to be fully realized. The examples of applications span from security to monitoring of consumption of facility resources. Furthermore, novel types of building performance measurement methods allow heterogeneous information generated within facilities, providing valuable information about the current state of a building. However, while extensive data is collected from constructed environments, there are still significant challenges in converting such data into useful information (Glaser & Tolman 2008).

The trend towards a more sensitive, adaptive, and responsive built environment has led to the concept of smart spaces. A smart space can be viewed as a physical environment in which smart objects collaboratively and continuously monitor the environment, interact with users, and adapt their behaviour according to information gathered from the physical environment (Cook and Das 2007). Additionally, different smart spaces are typically designed to work together in order to provide support for users throughout their different daily activities, contexts, and surroundings. The interoperability between smart spaces enables generalizing intelligent automation and decision-making capabilities to encompass heterogeneous environments, such as smart homes, offices, airports, shopping malls, or hospitals, through which an inhabitant may pass in daily life (Cook and Das 2007).

Alongside the present-day technological advances and the emergence of smart spaces, the traditional construction industry has been increasingly utilizing modern knowledge modelling methodologies and standards. In particular, Building Information Modelling (BIM) has attained widespread attention in the Architectural, Engineering, and Construction (AEC) industry, and it represents the process of development and use of a computer generated model to simulate the planning, design, construction, and operation of a facility (Azhar et al. 2008). BIM models are computer-generated data-rich and object-oriented representations of facilities, from which views and data appropriate to various users' needs can be extracted and analysed to generate information that can be used to make decisions, for example (Azhar et al. 2008; AGC Contractors' Guide to BIM 2006). The improved knowledge modelling promotes the adoption and realization of intelligent data-processing elements in the building industry as it facilitates the managing and sharing of the essential building design and project data in digital format throughout the building's life-cycle (Penttilä 2006).

Today, the vision of more intelligent and responsive spaces has expanded to new domains, such as vehicles and health care. For example, advanced smart sensor systems are increasingly being used in aerospace applications. These sophisticated data-collection systems will implement a range of sensing technologies to monitor conditions in both space vehicle environments and in aircraft or spacecraft operations (Hunter et al. 2008). Similarly, in the car industry, there is a motivation to design more intelligent transportation systems in order to achieve increased driver comfort, reduced traffic accidents, and increased traffic flow (Wu et al. 2009). As a result, the automotive industry has become increasingly interested in embedding sensing mechanisms that enable the car to make decisions for a safer and less expensive journey (Augusto et al. 2010). Furthermore, in the health-care industry, the emerging intelligent technologies are increasingly being utilized in determining the physical or cognitive status of an individual or in enhancing the ability of people with mental and physical challenges to lead independent lives in their own homes, for example (Pollack 2005; Cook and Das 2007).

In the domain of the built environment, the realization of smart spaces has revolutionized how buildings are managed from design through to occupancy. The overall management of smart spaces requires not only considering physical structures of buildings, but also understanding the collaboration and interdependencies between devices, services, and humans. Indeed, as a result of this diversity, efficient smart space life-cycle development and management requires the involvement of multidisciplinary teams of professionals that bring knowledge from their specific fields of expertise (Harper 2003). Additionally, multidisciplinary collaboration work contributes largely to the richness of diversity, which is shown to foster creativity (Fischer 2005).

As multidisciplinary teams are increasingly being implemented in the development and management of smart spaces, the actual work is more often globally organized, which promotes geographically dispersed teams. Organizations utilizing geographically dispersed, virtual teams are facing a sort of collaboration paradox. While they need to have a proper level of diversity to ensure a high level of creativity and innovation, more distance factors affect the overall collaboration performance (Pallot 2011). Members of distributed teams may have difficulty establishing a shared context, which may derive from and be revealed in different work and geographic environments, different technologies, and different cultures (Hinds and Bailey, 2003). Furthermore, the absence of shared context impedes the reaching of mutual understanding, which may significantly impact collaboration effectiveness and efficiency (Pallot et al. 2010; Clark and Brennan, 1991).

During recent years, promising technologies that attempt to overcome the collaborative distance have been developed both by the research community and industry. The resulting digital solutions aim to support design and development processes of products by fostering collaboration among multidisciplinary developers associated with the life-cycle of a product (Shen et al. 2008). Importantly, the solutions offer means for achieving deeper mutual understanding between collaboration stakeholders. For example, through data visualization, information and knowledge can be transformed into a visual form exploiting people's natural strengths in rapid visual pattern recognition, which leads to new insights and more efficient decision-making (Gershon et al. 1998). Although a picture says more than a thousand words, people will have different interpretations, which are often an incentive to communicate (Bekkers and Moody 2009). Hence visualization encourages and increases communication, which in turn facilitates learning (Henderson and McAdam 2003).

1.1 Motivation and background

The multidimensional smart space development and management work constitutes a set of tasks that involve complex technologies and usually require multidisciplinary and geographically distributed collaboration work. The successful execution of these tasks requires the involvement of numerous stakeholders with varying expertise, interests, and backgrounds (Cook and Das 2007). The contributing stakeholders encounter different kinds of challenges in different phases of a smart space life-cycle. For example, at the beginning of the development process, the focus is on achieving greater mutual understanding concerning such issues as "what are the most important requirements for a smart space" or "what kinds of technologies could be utilized". During the operational phase, an important objective is to create methods for acquiring information for different stakeholders about the operation of a smart space in terms of how well it is working and how the users experience it.

Currently, some approaches (e.g. Roalter et al. 2011, Dimakis et al. 2008, Wang et al. 2002) exist that are designed to facilitate smart space development and management. However, the existing tools are usually quite complex, requiring technical expertise for their use. Hence, they rarely provide comprehensive support for multidisciplinary collaboration work that also involves non-technical stakeholders. Furthermore, most of the existing approaches are bound to specific technologies, platforms, or applications, which constrict their utilization. Finally, the approaches are designed to address only certain parts of the smart space life-cycle.

In order to address the above-mentioned deficiencies, there is a need for more comprehensive support tools that help to overcome the technological barriers that hinder the contributions of especially non-technical stakeholders in collaborative activities related to smart space development and operation. With these tools, the multidisciplinary collaboration work can be supported by enhancing common understanding and providing ways of communication between collaborative stakeholders. Moreover, the tools should consider the specific requirements that are characteristic of different phases in the smart space life-cycle.

The hypothesis explored by this dissertation is that by creating supporting artefacts that efficiently utilize information visualization in the development and management of smart spaces, and by anchoring the visualizations into formal semantic data representations, the challenges related to multidisciplinary and geographically distributed collaboration work can be better managed. The utilization of appropriate visualization techniques and ontology representations enables different processes related to smart space development and management to become more understandable, which reduces the knowledge and communication gaps between collaboration stakeholders. The increased mutual understanding facilitates the ability of people with different educational backgrounds to contribute to the smart space development and management processes. Finally, by considering the entire life-cycle of smart spaces, the challenges related to the evolving nature and complexity of smart spaces can be better addressed.

1.2 Research objectives and questions

In this study, problems related to the multidisciplinary and geographically distributed development and management of smart spaces are discussed. The objective is to present methods for bridging distance factors that affect collaboration effectiveness and efficiency and that are generated by distributed and multidisciplinary collaboration work. The above-described challenges are addressed by, firstly, identifying the stakeholders that contribute to the development of smart spaces; secondly, determining their operational needs; and thirdly, discovering methods and techniques to support the stakeholders in the development and management of smart spaces in different life-cycle stages. In more detail, the following research questions are identified:

1. Who are the stakeholders that contribute to the development and management of smart spaces?
    a. What are the roles that different stakeholders have?
2. What are the needs and requirements of different stakeholders and how can they be addressed?
    a. What kinds of support means do the stakeholders find most useful?
    b. How can collaboration between stakeholders be supported?
3. What are the requirements that different life-cycle stages impose on smart space development and management?
    a. How can development and management of smart spaces in different life-cycle stages be supported?

1.3 Scope of the study

This dissertation focuses on the overall management process of smart spaces. More precisely, it examines the technical processes related to smart space development, construction, and operation in a multidisciplinary collaboration context. The final phases of the smart space life-cycle including disposal and re-cycling stages are out of the scope of this dissertation. Special attention is given to the utilization of visualization and semantic technologies in the knowledge creation process. Although the dissertation aims at representing methods and techniques that are applicable regardless of the context of a smart space, two special types of smart spaces are highlighted: smart homes and aeronautical final assembly lines. The selection of these particular focus areas was driven by the realistic use case scenarios that they provided. The use case scenarios not only inspired the research work, but also facilitated evaluating the research results.

The development and management of smart spaces involves numerous stakeholders who all have their unique needs, demands, and expectations. However, the focus of this dissertation is not to discuss detailed work process descriptions of different stakeholders. Instead, the aim is to address more general needs that different stakeholders may have. Additionally, although various functions provided by smart spaces are usually realized with different kinds of technical solutions, including sensors, actuators, software interfaces, and digital devices, a more thorough analysis of technical solutions designed for smart spaces is beyond the scope of this dissertation. Finally, a more detailed analysis considering the profitability or business impact of smart spaces is considered as beyond the scope.

1.4 Research strategy

As defined by Hevner and Chatterjee (2010), a research paradigm is “the set of activities a research community considers appropriate to the production of understanding (knowledge) in its research methods or techniques”. This dissertation utilizes the design science research paradigm in which questions relevant to human problems are answered via the creation of innovative artefacts, thereby contributing new knowledge to the body of scientific evidence. In design science, knowledge and understanding of a design problem and its solution are acquired in the building and application of an artefact (Hevner 2007). The artefact should improve upon existing solutions to a problem or perhaps provide a first solution to an important problem (Hevner and Chatterjee 2010).

Over time, information system research has produced knowledge by two complementary but distinct paradigms, behavioural sciences and design sciences (von Alan et al. 2004). Unlike behavioural science, which draws its origins from the natural science paradigm, and seeks to find the truth through testing hypotheses and developing theories, design science is fundamentally a problem-solving paradigm whose end goal is to produce and evaluate artefacts that address particular business needs (Hevner and Chatterjee 2010). To sum up, behavioural science searches for the truth, while design science seeks utility (von Alan et al. 2004). Furthermore, an important result of a design research process is information about how an artefact can be improved, is better than existing solutions, and can more efficiently solve the problem being addressed (Hevner and Chatterjee 2010).

Most of the existing natural science research methods are insufficient for the study of problems that require creative, novel, and innovative solutions, particularly in the management and information systems disciplines. Scientific theories may explain organizational phenomena, related organizational forms, and artefacts, but they cannot account for the qualitative novelty achieved by human intention, creativity, and innovation in the design of such artefacts. Design science provides a new way of thinking about what makes information system research relevant to its various audiences of managers, practitioners, and peer researchers in related fields. In design science, the process of understanding is changed from ‘what is’ to ‘what can be’ (Hevner and Chatterjee 2010).

As mentioned above, design science is primarily a problem-solving paradigm that calls for improving the effectiveness and utility of an artefact in the context of solving real-world business problems. In the field of information systems, design science research combines a focus on information technology artefacts with a high priority on relevance in the application domain. (von Alan et al. 2004)

Design science can be considered an especially suitable research paradigm for so-called ‘wicked problems’ (von Alan et al. 2004; Rittel and Webber 1973). As described in (von Alan et al. 2004), these problems are characterized by:

- unstable requirements and constraints based on ill-defined environmental contexts,
- complex interactions among subcomponents of the problem,
- inherent flexibility to change design processes as well as design artefacts
- a critical dependence upon human cognitive abilities (e.g., creativity) to produce effective solutions, and

- a critical dependence upon human social abilities (e.g., teamwork) to produce effective solutions.

As will be shown later, the development of smart spaces is definitely a good example of this kind of a 'wicked problem'. A smart space is a complex mixture of design and technology that evolves over time and is characterized by unstable requirements and complex interactions among components. Additionally, the development work of smart spaces demands high levels of creativity and constant innovation, and is usually performed in multidisciplinary and distributed teams.

A typical design research project includes three design science research cycles, which are represented in Figure 1.

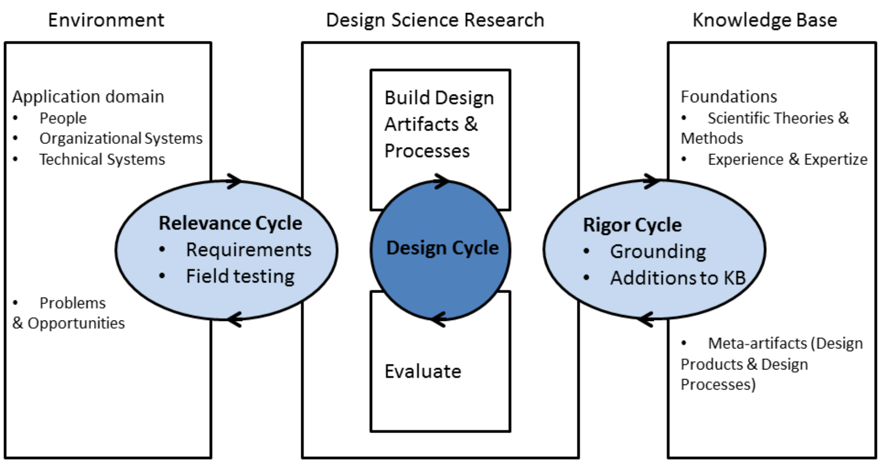

Figure 1. Design science research cycles (adopted from Hevner 2007)

The *relevance cycle* bridges the contextual environment of the research project with the design science activities. In the relevance cycle, requirements (e.g., the opportunity/problem to be addressed) for the research and acceptance criteria for the evaluation of the research results are defined. Considered questions are: 'Does the design artefact improve the environment?' and 'How can this improvement be measured?' The outputs of the research are returned into the environment for study and evaluation in the application domain. The results of the field testing determine whether additional iterations of the relevance cycle are needed (Hevner 2007).

Design science draws from a knowledge base of scientific theories and engineering methods that provides the foundations for rigorous design science research. In the *rigor cycle*, the design science activities are connected with scientific foundations that inform the research project. This encompasses considering the experiences and expertise that define the state of the art in the application domain of the research, and the existing artefacts and processes found in the application domain. The objective of the rigor cycle is, on one hand, to ensure that the designs produced are research contributions and not routine designs based on the application of known design processes and the appropriation of known design artefacts, and on the other hand, to make sure that the research is grounded on existing ideas drawn from the domain knowledge base (Hevner 2007).

The *design cycle* is the heart of the design science research, iterating between the construction of an artefact, its evaluation, and subsequent feedback to refine the design further. Whereas the requirements are input from the relevance cycle, and the design and evaluation theories and methods are drawn from the rigor cycle, the design cycle is where the hard work of design science research is done. In the design cycle, it is essential to maintain a balance between the efforts spent in constructing and evaluating the evolving design artefact (Hevner 2007).

As earlier mentioned, this dissertation follows the design science research paradigm. The core of the dissertation is the research papers, in which the performed research work and the resulting research artefacts are represented and described. These design science research cycles guided the research work that was carried out as an iterative process. Each of the iterations focused on producing artefacts that provide support for a certain smart space development phase and certain stakeholder roles. Figure 2 represents the iterative design cycle that was utilized in this dissertation.

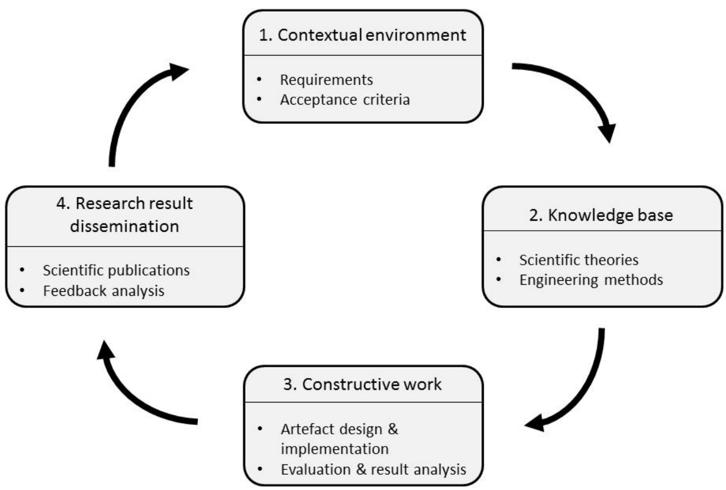

Figure 2. The iterative design cycle applied in the dissertation

The research work was carried out iteratively in the context of international research projects that studied the development and management of smart spaces. The knowledge and experiences gained from these projects served as a basis for deriving requirements related to the different phases of the smart space life-cycle, addressing also the multidisciplinary and distributed nature of the smart space development and management work. Moreover, this contextual environment supported defining acceptance criteria for the evaluation of the created artefacts (e.g. ‘Does the constructed artefact support sufficiently different stakeholders in the development work of smart spaces?’ and ‘How this can be measured?’).

The knowledge base of the domain was researched in order to find scientific theories and/or engineering methods that provide foundations for the research work. Additionally, by conducting a literature review it was ensured that no similar approaches have been delivered by the research community or industry. In the construction phase, an artefact that supports smart space development work was implemented and evaluated. The evaluation consisted of, for example, performing tests with potential end-users and analysing the test results. In the final phase, the research results were published in scientific forums and the feedback received from the scientific community was analysed. This feedback, as well as the results provided by the evaluations, served as an input for the next iteration cycle.

1.5 Structure of the dissertation

The purpose of Chapter two is to introduce the smart space development process. The collaboration distance framework that clusters various distance dimensions and related factors appearing in the course of distributed collaboration is discussed in Chapter three. The existing state of the art of approaches used for supporting smart space development and management is introduced in Chapter four. Chapter five introduces the most important requirements identified in the artefact development processes. Moreover, the basic components, as well as the interactive visualization features of the artefacts are represented. Chapter six summarizes the included publications and the author’s contribution to them. Chapter seven contains an evaluation of the results of this dissertation. In Chapter eight, the artefacts are analysed against the collaboration distance framework. Finally, the ninth chapter presents the conclusions and the future research related to the achieved results.

2. The development and management of smart spaces

The purpose of this chapter is to discuss the development and management processes of smart spaces and illustrate the existing state of the art of relevant approaches that aim to support the smart space development and management process. First, the chapter introduces the roles that different stakeholders have in smart space development and management. Second, the life-cycle of smart spaces is introduced.

2.1 The concept of smart space

Numerous definitions exist for the concept of smart space. For example, in Cook and Das (2007), a smart space is viewed as a physical environment in which smart objects collaboratively and continuously monitor the environment, interact with users, and adapt their behaviour according to information gathered from the physical environment. Similarly, a smart space is defined as a dynamic environment whose identity changes over time when the set of entities interact with it to share information between them (Saleemi et al. 2012). Moreover, Ma et al. (2005) define smart space as a space that must have some kinds of levels of abilities of perception, cognition, analysis, reasoning, and anticipation about a user's existence and surroundings, on which it can accordingly take proper actions.

In many ways the concept of smart space is similar to the concept of ambient intelligence, which refers to the presence of an environment that is sensitive, adaptive, and responsive to the presence of people or objects (Boekhorst 2002). Smart spaces are able to provide such information about physical environments that can be shared with inherently dynamic applications, which in turn enables ubiquitous ambient services to better adapt themselves to different user preferences in each particular context (Saleemi et al. 2012). Because appliances and devices usually disappear into the environment, in smart spaces services come into focus instead (Weber et al. 2003). Thus, ambient intelligence systems are often designed using a service-oriented approach, in which devices in the environment provide independent services. By composing distributed services, Service-Oriented Architecture (SOA) makes it possible to supply clients with more complex services that are able to adapt to changing situations (Vallée et al. 2005).

As earlier mentioned, the realization of smart spaces requires merging the material and digital worlds by incorporating physical and computing entities into the same dynamic environment. The conversion of an ordinary building or a space, such as a home, workplace, classroom, or vehicle, into a smart space requires the use of embedded sensors, augmented appliances, stationary computers, and mobile handheld devices to gather information about users' locations, companions, and other aspects of their activities, for example (Wang et al. 2002). Different applications operating in such environments must also be context aware so that they can adapt to rapidly changing conditions (Dey 2000).

The adaptation of applications and services to changing situations requires the existence of a detailed model of users' activities and surroundings that enables sharing users' perceptions of the real world (Henricksen et al. 2002). Often, this kind of context model is created using semantic technologies, especially ontologies, as they provide effective machine-to-machine communication capabilities enabling computational entities and services to have a common set of concepts and vocabularies for representing knowledge about a domain of interest. Context ontologies provide a foundation for building interoperable smart spaces where computing entities can easily exchange and interpret contexts based on explicit context representation (Wang et al. 2002).

The importance of ontologies has been recognized in many diverse research fields of computer science for several years and ontologies have gained a specific role in, for example, artificial intelligence, computational linguistics, and database theory (Guarino 1998). A commonly agreed definition of ontology, made by Gruber (1993), is the following: "An ontology is an explicit and formal specification of a conceptualisation of a domain of interest". Furthermore, ontology is defined as a controlled vocabulary that describes objects and the relations between them in a formal way; ontology resembles faceted taxonomy but uses richer semantic relationships between terms and attributes, as well as strict rules about how to specify terms and relationships (Uschoold and Cruninger 1996; Lijun et al. 2006; Berners-Lee et al. 2001).

Smart space development and management has been defined as the collection of all activities that ensure secure and effective usage, operation control, administration, and maintenance of a smart space, including all its devices and smart services, as well as relationships to external devices and services (van der Meer et al. 2003). Moreover, a major goal in the development and management of smart spaces is the realization of software, systems, and services that address composition, scalability, reliability, and robustness, as well as autonomous self-adaptation within a smart space's complex environment (Ghamri-Doudane et al. 2004). Hence, it can be stated that smart space development and management is a process that continues throughout the entire life-cycle of smart spaces and involves a variety of stakeholders with different responsibilities and roles.

2.2 Stakeholder roles

By definition, a stakeholder is any one that has a stake in the project or its outcome. Stated differently, it is an individual, team, organization, or classes thereof, having an interest in the realization of a system (Rozanski and Woods 2011). The overall management process of smart spaces involves numerous stakeholders coming from different disciplines, including pervasive and mobile computing, sensor networks, artificial intelligence, robotics, multimedia computing, middleware, and agent-based software (Cook and Das 2007). A characteristic of a smart space is that it evolves after its deployment as spatial configurations are changed or new services or products are added, for example (Ovaska et al. 2011). The evolving nature of smart spaces requires that possible changes are managed in a way that makes a smart space attractive for its application providers, users, and other stakeholders (Ovaska et al. 2011). Moreover, new risks and conflicts that could arise due to changed configuration highlight the importance of safety issues that need to be constantly managed during the entire life-cycle (Chen et al. 2012).

As described above, the development and management of smart spaces is a demanding process and requires a multitude of stakeholders with multidisciplinary skills and knowledge. In addition, the development and management of smart spaces covers the entire life-cycle, from initial design to maintenance. Different stakeholders of smart spaces have diversified roles that determine their responsibilities and rights. It is essential to notice that the roles are generalized representations of different stakeholders and a single stakeholder may have multiple roles.

In the following sub-chapters, a list of identified stakeholder roles is described in more detail. A majority of the role descriptions are adopted from the research conducted by Chen et al. in 2012. However, because of the evolving nature of smart spaces and the active involvement of end-users in the development process, the stakeholder list is extended with two additional role descriptions: smart space user and maintenance worker.

2.2.1 Space owner

Space owners either own or occupy the physical property and usually set the goals and define the purpose of a smart space under development. Additionally, space owners are either direct end-users of a smart space (e.g. a residential building) or organizations that provide smart spaces (e.g. retail spaces, smart buildings, special education centres, monitored asset sites, energy-managed installations) for target users. Smart space owners are usually aware of the needs of users and hence they are often engaged in the planning and design phases and represent the user requirements in negotiations. Space owners are also responsible for specifying a budget for a smart space and hiring a general space developer and administrator personnel (or service) to be in charge of the monitoring and maintenance of the space (Chen et al. 2012).

2.2.2 General space developer

General space developers have the knowledge and expertise necessary to take charge of the overall design and deployment of a smart space, including requirement specification, architectural design, and implementation. They need to understand the end-user needs, as well as have the resources to acquire and integrate various components, and implement solutions that address those needs. Space developers usually work in close collaboration with space owners (and/or users) in order to formulate requirements that meet the goals of owners and users. Moreover, space developers select and possibly purchase the most appropriate components for a smart space, including middleware, services, and devices. Sometimes space developers are responsible for hiring people to perform physical installation and deployment tasks, and to connect and integrate diverse components. To conclude, general space developers are in charge of coordinating the different roles needed at the various stages of the life-cycle of smart spaces (Chen et al. 2012).

2.2.3 Space administrator

The role of a space administrator is to perform the necessary adjustments that take place after the initial deployment of smart spaces. These adjustments encompass such re-configurations as device changes and service upgrades, for example. The space administrator’s role also covers diverse monitoring and response services, as well as the handling of emergencies and other events that require human intervention or instruction (Chen et al. 2012).

2.2.4 Space technician

A space technician works under space developers and is responsible for managing the infrastructure of a smart space. The role covers such tasks as setting up networks, installing servers, controllers, and personal computers, and wiring the sensors and actuators according to the specifications made by space developers (Chen et al. 2012).

2.2.5 Device manufacturer

Device manufacturers supply the necessary smart space components, including sensors, actuators, controllers, and networks, for example. In order to make the supplied devices available to various smart space services and applications, device manufacturers must also provide detailed specifications of device interfaces and protocols (Chen et al. 2012).

2.2.6 Middleware provider

The purpose of a middleware solution is to host and seamlessly integrate a variety of software services and hardware devices that realize the objectives of a smart space. To achieve this, a middleware provider must supply software tools that convert device specifications into software services, allowing access and control to devices via standards-based service interfaces. Additionally, middleware providers have to provide tools and user interfaces that enable space administrators to install, configure, and maintain the system at runtime (Chen et al. 2012).

2.2.7 Service provider

The service providers' responsibility is to implement necessary software services according to requirement specifications. The service implementation encompasses either developing new or highly customized services or reusing pre-existing services. The service provider also carries responsibility for informing space developers and administrators about dependencies between services. The dependence relationships can affect the decisions about which services to include and which to exclude from a final smart space configuration (Chen et al. 2012).

2.2.8 Smart space user

As mentioned earlier, a smart space user is either the owner of the space or an individual who interacts with the space and takes advantage of the services it provides (Friday et al. 2001). Additionally, smart space users have a critical role in the development phase, as they are able to provide valuable insights for developers about their needs and expectations (Durrett et al. 2002).

2.2.9 Maintenance worker

The main responsibility of a building maintenance worker is to take care of routine repairs and remedial actions. These tasks are usually carried out at intervals in order to keep different spaces in an appropriate condition. Moreover, this work may involve either the repair or replacement of an item and is generally necessitated by natural deterioration or normal wear and tear. Additionally, maintenance workers often have to perform different kinds of inspections. These inspections are normally carried out in order to identify items in need of repair or replacement. A systematic inspection procedure usually requires using different kinds of aiding tools that include, for example, checklists that clearly set out the criteria for classifying the condition of particular elements (Chanter and Swallow 2008).

2.3 The life-cycle of smart spaces

The realization of a smart space can be considered as a construction process, in which the necessary physical infrastructure and intelligent services are being designed and established. In general, construction projects pass through three major life-cycle phases, which are design, construction, and operations (Succar 2009). However, in order to emphasize the importance and magnitude of early stages of the smart space life-cycle, the term design is replaced with a broader term development in this dissertation.

The utilization of modern intelligent technologies and the growing amount of available information require new ways of managing environments. Modern buildings containing smart elements are not considered as individual objects, but instead as parts of larger systems, allowing complex and mutually beneficial interactions between the built environment, the living world, and human inhabitants. Moreover, it must not be forgotten that a constantly dynamic and responsive built environment evolves over time (Jenkin and Zari 2009).

The administration of modern buildings can be considered similar to the management of evolving business processes or information systems, in which effective management requires considering the entire life-cycle, which involves everything from capturing the process in a computerized representation to automating the process (Georgakopoulos and Tsalgatidou 1998; Vanlande et al. 2008). The life-cycle of smart spaces can be divided into different phases, where each stage is generally managed independently and is divided into superimposed layers (Vanlande et al. 2008). In Figure 3, the three main phases of the smart space life-cycle are represented.

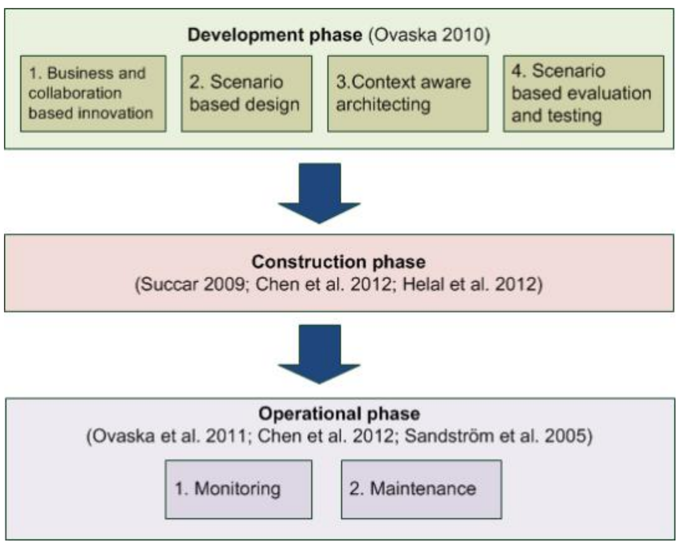

Figure 3. The phases of the smart space life-cycle

The following sub-chapters provide more detailed descriptions of each of the stages.

2.3.1 Development phase

An OPSE (Ontology-driven Piecemeal Software Engineering) approach (Ovaska 2010) represents a novel and well-established way to conduct a smart space development process in four phases. The core of the OPSE framework is the assets repository (Niemelä et al. 2005), called a smart space knowledge base, which embodies knowledge in the form of ontologies, exploited in a set of software engineering phases: i) business and collaboration-based innovation inspired by software product line engineering (Pohl et al. 2005); ii) scenario-based design that brings the user's viewpoint to the design (Ikonen 2005); iii) context-aware architecting based on model-driven engineering and semantics modelling (Bettini et al. 2010); and iv) scenario-based evaluation and testing (Ovaska et al. 2010). Next, each of the phases is described in more detail.

2.3.1.1 Business and collaboration-based innovation

The objective of business and collaboration-based innovation is configuring and adapting the behaviour of the building blocks of smart spaces. The purpose of the intended smart space is defined from business and organisation points of view by answering such questions as: Is the space to be profitable? Is the main goal to provide enhanced experiences to its users or something else? How are business impact, markets, and acceptability of the smart space estimated? The business and collaboration-based innovation phase typically includes such activities as defining the purpose and boundaries of the smart space and performing the necessary impact, risk, and asset analysis (Ovaska 2010).

2.3.1.2 Scenario-based design

User orientation is the obligatory feature of all smart spaces and therefore, user-centric design of smart spaces benefits from common reusable or adaptable usage patterns and profiles. Patterns are used as building blocks, for example, in smart application development for adapting and configuring generic application models for particular usage scenarios (Ovaska 2010; Ovaska et al. 2010). Patterns can be developed for role-based adaptation and security-based adaptation, for example (Ovaska 2010). Profiles are merely used for run-time configuration and adaptation with domain or usage-specific properties and for evaluating and testing usage scenarios (Ovaska 2010). The utilization of patterns and profiles benefits the development of smart spaces as user-centric design and context-aware execution are crucial properties of smart spaces (Ovaska 2010).

In smart space development, scenarios can also benefit the discovery of more concrete requirements. Requirements definition is the process of identifying, defining, and documenting specific needs for the development of a new product, system, process, or service (Sanchez 1998). Due to a dynamic design environment consisting of emergent technology, with minimal existing systems to evaluate, few standards, and users with vague ideas of the benefits or the possibilities, determining accurate requirements for smart spaces is difficult (Durrett et al. 2002). When specifying requirements of smart spaces, a primary concern is communication and mutual understanding between different stakeholders, such as administrators, technicians and smart space users. With scenarios, implications of alternative futures, especially as they might be impacted by new technologies, can be analysed (Ovaska 2010). Additionally, scenarios facilitate presenting users with a viewpoint of potential capabilities to enable users to visualize what a smart space might do for them (Durrett et al. 2002).

2.3.1.3 Context-aware architecting

An information system architecture is a formal definition of a system that is decomposed into components, how these components are interconnected, and how they communicate and interact with each other (Soni et al. 1995). Typically, architectural views are used for different purposes, such as for describing structure, behaviour, and deployment. The starting point of architecture specification in the OPSE framework is to facilitate the creation of components by different stakeholders, not only by architects (Ovaska 2010). These components may be different kinds of artefacts: ontologies, models, patterns, metrics, guidelines, and source code (Ovaska 2010). The purpose of the created components is to facilitate the knowledge creation and usage in an incremental and long-lasting development and evolution of smart spaces (Ovaska 2010). An important aspect of context-aware architecting is also to solve how situation-based behaviour in smart spaces is to be realized (Ovaska 2010). The objective is to develop an ontology-driven (architecture) knowledge base that helps in different development phases of smart spaces (Ovaska 2010).

Smart spaces embody service orientation and dynamism that can be triggered by any change in the user’s intent, or the external or internal behaviour of the space. Therefore, the architectural ontologies consist of such ontologies that define the functional and quality properties of services and data, and the context ontology, for example (Ovaska 2010). The context ontology can be divided into three levels, which are physical, digital, and situational (Pantsar-Syvaniemi et al. 2010). The physical level defines the physical entities and the information they provide, the digital level describes the digital entities (e.g. services and applications), and the situational level encompasses higher-level context information that is referred to as a situational context (Pantsar-Syvaniemi et al. 2010; Ovaska 2010). The higher-level context information (e.g. what is the user doing) is usually inferred from low-level, explicit contexts provided by hardware sensors (Dey and Abulaish 2008).

The context information that in OPSE is described using ontologies has to be presented in a machine understandable format, often also in a human understandable format (Pantsar-Syvaniemi et al. 2010). An effective method is the Web Ontology Language (OWL) semantic mark-up language, which was created for publishing and sharing ontologies, providing mechanisms for creating all the components of an ontology: concepts, instances, relations, and axioms (Davies et al. 2006). In smart spaces, computational entities need to be context-aware so that they can adapt themselves to changing situations (Wang et al. 2004). The requirement of context-awareness brings an increasing need for developing formal, ontology-based context models that facilitate context representation, context sharing, and semantic interoperability of heterogeneous systems (Wang et al. 2004).

An important benefit of context ontologies is also their ability to facilitate common understanding between members of a collaborative team. As discussed earlier, the development of smart spaces usually involves a virtual organization team with dispersed members working on a single project (Vanlande et al. 2008). The existence of a gap in the communication between different stakeholders always brings about a failure in real development (Lertlakkhanakul et al. 2008). The comprehension among stakeholders and the ability to share perceptions of the real world can be enhanced with an information model that describes users' activities and surroundings in a structured way (Henricksen et al. 2002). This kind of context model can also facilitate delivering design ideas to the end-users of smart spaces (Henricksen et al. 2002; Lertlakkhanakul et al. 2008).

2.3.1.4 Scenario-based evaluation and testing

Similarly to the scenario-based design of smart spaces, evaluation and testing are also performed using scenarios. The scenario-based evaluation of smart spaces is often inspired by work on scenario-based analysis (Kazman et al. 1996) of software architectures, in which scenarios enable the expression of particular instances of a quality attribute important to specific life-cycles of an application (Bischoff et al. 2007). During the test process, each quality attribute is estimated, using primarily scenario-based analysis as an assessment technique. An important objective of scenario-based evaluation is to guarantee that user satisfaction is achieved and the business and collaboration rules are followed (Ahonen et al. 2010).

In computer science, a scenario is a description of interactions between users and the system, describing how the system will be used in daily activities (Weidenhaupt et al. 1998). In scenario-based evaluation, scenarios can be used as part of the development process as a common example of how the system should work, thus enabling developers to target development and testing resources at appropriate areas (Looker et al. 2008). The scenario-based evaluation process of information system quality can be divided into different steps, which are, for example, defining a representative set of scenarios, analysing the performance of the architecture in the context of the defined scenarios, and summarizing the results. As an outcome of the evaluation, the number of accepted scenarios versus the number not accepted should be known (Weidenhaupt et al. 1998).

In many cases, simulation is an important part of testing. Especially in smart spaces, where the development usually requires integrating many heterogeneous devices and service applications, the complexity of the domain determines that it is difficult to test. Problems discovered late in the process are expensive to correct because they may require time-consuming software programming and hardware fixes (Lei et al. 2010). By using simulations, some parts of use-case scenarios, or a certain set of features and functions of smart spaces, can be verified and tested without the need to set up an environment with real products and sensors (Lei et al. 2010; Helal et al. 2012). Simulation enables the evaluation of alternative design concepts, validation of interfaces and functions, justification of early design decisions, and display of scenarios and device states (Lei et al. 2010; Niskanen and Kantorovitch 2011; Miller and Pegden 2000).

2.3.2 Construction phase

Once the design and development work is complete, the next logical step is to construct the necessary infrastructure for realizing the smart space functions. Commonly, the construction phase in a construction process encompasses such activities as construction planning and detailing, and manufacturing and procurement (Succar 2009). In smart spaces, the effective use of physical components such as sensors, controllers, and smart devices is vital because sensors enable us to observe, monitor, and interact with the physical world in real time, and also enable us to take appropriate actions (Cook and Das 2007). Without these physical components, we end up with theoretical algorithms that are of limited or no practical use (Cook and Das 2007).

The nature and practical implementation of the smart space construction phase depends on the type of the smart space in question. For example, unlike the production processes of matured conventional industries, which typically have product-lines providing end-to-end solutions for the manufacture and assembly of final products, the creation of a smart house is usually more of an ad-hoc process with a lack of consistent standards and methods (Chen et al. 2012). Furthermore, building a smart house involves a multidisciplinary team of technicians, programmers, electronic engineers, computer scientists, and domain experts who have to work in collaboration to reach the objectives set for the construction phase (Helal et al. 2012). The necessary activities performed by different specialists encompass such tasks as ordering software and hardware components from various providers, setting up networks, installing servers, controllers, and personal computers, connecting the various sensors and actuators to the pervasive applications, creating abstract software services representing different hardware devices, and setting up middleware that connects applications with devices (Chen et al. 2012).

As discussed earlier, modern vehicles such as aircraft can also be considered as smart spaces as they contain a variety of different sensors that monitor and provide dynamic information about physical conditions and are able to adapt to changing situations (Hunter et al. 2008). Unlike smart houses, the construction processes of smart vehicles are typically carried out using well-established production lines where tasks are similar and relatively static. For example, in Publication 4, an aeronautical final assembly line in which an aircraft goes through several stages before completion is described in more detail. The assembly process involves numerous stakeholders who perform assembly tasks collaboratively, and the process is guided by a workflow that specifies the exact steps required to complete various activities. Additionally, in general, the construction processes of smart vehicles are usually supported with digital solutions designed to facilitate the orchestration and implementation of collaborative activities (Streitz et al. 1999).

2.3.3 Operational phase

The final phase in the life-cycle of smart spaces is the operational phase. The operational phase can be divided into two sub-phases, which are smart space monitoring and smart space maintenance.

2.3.3.1 Monitoring

The objective of smart space monitoring is to gain understanding about the operation of a space (Ovaska et al. 2011). In order to gain the maximum benefit of the space, different stakeholders usually have diversified objectives for smart space monitoring. For example, space owners are mostly interested in how users experience the space, service/information providers are interested in how well the space is working and how many potential users are visiting the space, and smart space developers want to see how the space behaves under normal and stress operations (Ovaska et al. 2011). Additionally, the monitoring can serve objectives of external actors who are interested in gaining information about the functioning of a smart space. For example, caregivers or relatives may want to examine if a smart space is able to enhance the quality of life of elderly people, afford them a greater sense of security, and facilitate independent living (Sixsmith and Johnson 2004).

The monitoring of smart spaces is usually supported by a technical infrastructure with IT systems that automatically connect smart home systems at a distance. The technical infrastructure should make it possible to remotely check the status of the system, become informed automatically of any malfunction or defect in the system, maintain and upgrade the system on site on a regular basis, be able to assist on the site with minimal delay, and give around-the-clock support online (Sandström et al. 2005).

2.3.3.2 Maintenance

A characteristic of smart spaces is that they evolve over time as new technologies emerge or as an application domain matures, for example (Helal et al. 2012. The maintenance phase aims to address the challenges brought about by the changing nature of smart spaces. The maintenance includes such tasks as updating software, replacing defective devices, and responding to critical conditions in the space (Chen et al. 2012). Moreover, the needs and preferences of users may change over time, which may require, for example, adapting existing services and/or installing new services into a smart space (Crotty et al. 2009). The maintenance phase also requires updating documents created during the design and development phases whenever maintenance operations are carried out (Chen et al. 2012).

3. Collaboration distance framework

The general trends in today's work life are shifting towards more global business environments and ever more complex working patterns that are supported by advanced information technologies (Pallot 2011). The globalization effect and the development of more efficient information processing systems foster the trend of globally organized work, which in turn promotes geographically dispersed teams as the main configuration style within many organizations (Lu et al. 2005). However, it is argued that that geographic distance implies differences in time, language, culture, and organizational processes that negatively impact team coherence and work practices (Lu et al. 2005). Additionally, virtual work that is work that crosses space, time, organization, culture, and media has been perceived to cause discontinuity and have negative impact on efficiency, mostly because of the increased challenges in communication and coordination (Clark and Brennan 1991; Watson-Manheim et al. 2005).

The most important aspect to be considered when discussing collaborative work is the distance between collaborative individuals. While nearness or proximity can facilitate communication and social interaction, greater distance can have the inverse effect (Pallot 2011). Because the members of distributed teams are distant from each other, they may have difficulty establishing a shared context, which may derive from and be revealed in different work and geographic environments, different technologies, and different cultures (Hinds and Bailey 2003). In the absence of the shared understanding of external and internal worlds, team members usually have difficulty developing mutual understanding (Clark and Brennan 1991).

The importance of shared context is highlighted in innovative and competitive working environments where communication, including integration of specialized knowledge and negotiation, has emerged as a fundamental component of design processes (Sonnenwald 1996). When teams include participants from different disciplines, organizations, and cultures, they may have pre-existing patterns of work activities, specialized work languages, and different expectations and perceptions of quality and success, and different organizational constraints and priorities (Sonnenwald 1996).

Although there are still major challenges in creating mutual understanding between people with different backgrounds, promising technologies that attempt to overcome the collaborative distance between experts have been developed over time (Holmstrom et al. 2006). For example, Computer Supported Collaborative Design (CSCD) aims to support processes in which products are designed through collaboration among multidisciplinary product developers associated with the entire product life-cycle (Shen et al. 2008). CSCD is required to support distributed design where specialists work in parallel and independently using different engineering tools, distributed at separate locations and across various time zones around the world (Shen et al. 2008). In CSCD, information and communication technologies are used to augment the capabilities of the individual specialists, and enhance the ability of collaborators to interact with each other and with computational resources (Shen et al. 2008).

Despite the challenges, the distributed collaboration work also brings benefits. For example, studies suggest that international collaboration that involves individuals from different cultures supports higher creativity and innovativeness due to a larger diversity of expertise (Cummings and Kiesler 2005; Fay et al. 2006). Distributed teams also enable organizations to take advantage of expertise around the globe, to continue work around the clock, and to create closer relationships with far-flung customers (Hinds and Bailey, 2003). Moreover, the realities of today’s business environment often dictate that the efficient use of distributed teams may be the only viable option for achieving organizational goals (Hinds and Bailey, 2003).

The distributed collaboration in which professionals work across distance, time-zone differences, and culture, generates distance factors that affect collaboration effectiveness and efficiency. Different distance factors are considered in more detail in a holistic framework called ‘Collaborative Distance’ (Pallot 2011). The framework clusters various distance dimensions and related factors appearing in the course of distributed or distant collaboration. The examination of dispersions in multiple dimensions improves the ability to understand teams and technology use within them (O'Leary and Cummings 2007).The identified distance factors can possibly be overcome by creating some sort of proximity, which might be achieved by, for example, using temporary collocation to create geographic proximity, or by applying the same collaboration tools or standards to enable interoperability among tools and applications to create technological proximity (Pallot 2011).

The ‘Collaborative Distance’ framework groups different distance types into four logical dimensions of distributed collaboration among knowledge workers: structural, social, technical, and legal and ethical. The identified distance factors are grouped into dimensions, as shown in Figure 4.

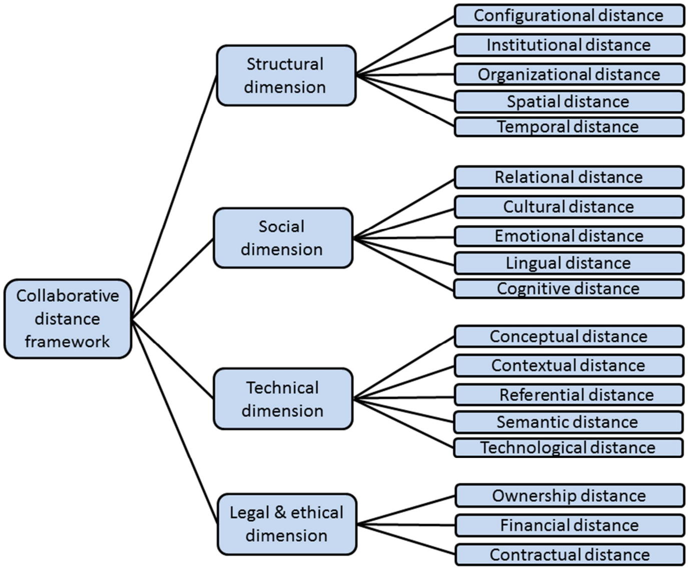

Figure 4. Collaborative distance factors (Pallot 2011).

Below, the four logical dimensions of distributed collaboration work, with associated distance factors, are described in more detail.

3.1 Structural dimension

The structural dimension includes five distance types: configurational, institutional, organisational, spatial, and temporal. Essential for the structural dimension is supporting collaboration activities with various arrangements in space and time. For example, providing asynchronous communication means is a fundamental prerequisite for effective distributed teamwork (Pauleen and Yoong 2001). At the same time, synchronous communication is also occasionally needed, which can be supported by web-conferencing or online chat applications, for example (Pallot 2011).

3.1.1 Configurational distance

The configurational distance refers to the arrangement of team members across sites of the same or different organizations, where a site is the building, office campus, or city where one or more team members are located (O'Leary and Cummings 2007). Essential for the configurational distance is the distribution of resources, expertise, and R&D work, and the team members' feeling of isolation, which can possibly be minimized through communication technologies that increase their sense of connectedness and involvement, as the isolation potentially decreases awareness of other team members' activities (Grinter et al. 1999; O'Leary and Cummings 2007). The configurational distance initiated by large number of distributed sites also creates coordination complexity, for example, in terms of how power and expertise in decision-making are balanced across sites (Baba et al. 2004; Ancona and Caldwell 1992).

3.1.2 Institutional distance

The institutional distance can be defined as the difference/similarity between two institutional environments, in which an institutional environment is operationalized as a three-dimensional construct including regulatory, cognitive, and normative dimensions (Kostova 1996). Institutional distance is closely related to regional contextual developments and to country-specific regulations that impact collaboration performance (Filippi and Torre 2003; Barkema et al. 1997). Organizations are also heavily influenced by common understandings of what is appropriate and, fundamentally, meaningful behaviour (Zucker 1983). The institutional system of a region determines its levels of education, technological development, and economic development (Li and Scullion 2006).

3.1.3 Organization distance

Organization distance refers to differences in organizational cultures that encompass the norms and values of an organization and include the culture of systems development, such as the use of methodologies and project management practices (Carmel and Agarwal 2001). The organizational distance sets requirements for coordination and management, since employees of different organizations are used to different information systems (e.g. knowledge bases, calendars) and communication channels, and are trained in specific corporate methodologies, policies, and systems that may impede interoperability (Carmel and Agarwal 2001; Pallot et al. 2000).

3.1.4 Spatial distance

Spatial distance is the geographic distance between collaboration stakeholders and it can be objectively measured in kilometres or miles. Regardless of the units of measurement, geographically dispersed teamwork requires that at least two members are separated by spatial distance (O'Leary and Cummings 2007). Several factors advocate the use of geographically dispersed teams. For example, geographically dispersed, virtual teams allow organizations to respond faster to increased competition because they can quickly harness the knowledge employees possess, regardless of location (Bell and Kozlowski 2002). Virtual teams are particularly effective when tasks become more complex, because complex tasks often require multiple individuals, each with an area of expertise, to coordinate their actions, and often this expertise is located outside an organization (Bell and Kozlowski 2002). Organizations may also want to decrease the costs of office real estate and the cost to employees (in time and stress) of commuting (O'Leary and Cummings 2007).

Spatial distance has strong effects on spontaneous face-to-face communication, and thus the interaction between team members becomes crucial (Bell and Kozlowski 2002). Although ICT technologies enable new forms of collaboration, they do not necessarily provide effective means of communication between team members, especially when a task is very complex and requires a great deal of information exchange and group decision-making (O'Leary and Cummings 2007; Bell and Kozlowski 2002).

3.1.5 Temporal distance

Time distortion between team members' normal work hours is caused by collaboration across several times zones or across several working shifts, or through redesign and evolution by people not necessarily involved in the earlier stage of a design process (Fischer 2004; Finholt et al. 2002). Temporal distance makes synchronous interaction less common and more difficult, generally exacerbates the challenges of coordination, and hinders real-time problem solving (O'Leary and Cummings 2007). Design processes may also take place over many years, with initial design followed by extended periods of evolution and redesign, and often the people doing this work are not members of the original design team (Fischer 2004). In these situations, the people carrying out the redesign work need to be able to collaborate with the original designers and be aware of the rationale behind their decisions (Fischer 2004). The speed and complexity of the modern business environment require organizations to use teams with temporal constraints. For example, in many cases, companies need to provide customer service on a global basis (i.e., to customers in different time zones and on different schedules) (O'Leary and Cummings 2007). Temporal distance may also benefit professionals, as performance-reducing interruptions are most likely to be inhibited by high degrees of temporal dispersion (O'Leary and Cummings 2007).

3.2 Social dimension

The social dimension comprises five distance types, which are relational, cultural, emotional, lingual, and cognitive. All the distance types are related to social interaction factors that mediate both the creative activity and the exchange of information, and facilitate or hinder mutual understanding (Cecez-Kecmanovic and Webb 2000; Luck and McDonnell 2006). Social activities among team members are also a prerequisite for trust building, which is essential for effective teamwork (Zucker et al. 1995). Moreover, social activities enhance team awareness by enabling team members to become aware of each other's current and future activities, for example (Schäfer et al. 2004). While team awareness in face-to-face workspaces is relatively easy to maintain, awareness in virtual workspaces is often very difficult to obtain. Support for team awareness, as well as mutual understanding and trust building in dispersed teams, has been tried with various information technology solutions that, for example, communicate work context, agenda, and workspace information to the involved team members just in time and using compatible interfaces (Ferscha 2000; Kasper-Fuehrera & Ashkanasy 2001).

3.2.1 Relational distance

Relational distance refers to the way people build relationships with one another (Pallot 2011). It is also related to the difference between team members' organizational affiliations, so that, for example, an employee of a company is relationally closer to another employee of the same company versus an outsourced employee (Lojeski et al. 2006). Relational distance between virtual team members can be measured in different ways, for example, by defining it as the relative position in a given social network (i.e. the network member that is mentioned first, second, etc.), where the order in which members are mentioned implies a larger relational distance (Tillema et al. 2010). Additionally, the way people characterize their relationship with another person (a relative, a good friend, a good colleague, a distant friend, or an acquaintance) indicates how small the relational distance between them is (Tillema et al. 2010). Often, close relationships are built in informal settings where team members share practical experiences (Wenger 1998). Relational distance also affects how people interact with each other. For example, it has been discovered that asynchronous modes (in particular email) become more influential as the relational distance increases (Tillema et al. 2010). Current social networking applications enable individuals to maintain existing relational ties or build new ones, thus increasing the ability to make new friends at a distance (Pallot 2011).

3.2.2 Cultural distance

Cultural distance hinders mutual understanding and communication among people involved in distributed work, and living in different regions of world (Armstrong and Cole 2002). Cultures can have a huge effect on how people communicate information or how they interpret a certain situation, and how they react to it (Ma et al. 2006). Despite the challenges caused by cultural distance, it also contributes largely to the richness of diversity, which has been shown to foster creativity (Fischer 2005). Thus there is a paradox between a homogeneous group, where it is easier to reach a mutual understanding but there are fewer creative stimuli, and a heterogeneous group, where it takes longer to reach a mutual understanding but which provides more creative impetus (Boland and Tenkasi 1995).

3.2.3 Emotional distance

Emotional distance indicates how well team members are able to perceive each other's emotional state or socio-emotional exchange (Goleman and Kankaanpää 1999; Damian 2001). The inability to observe another person's feelings can disturb or impede the collaboration process (Glover 2000). In dispersed teams where most of the collaboration work is carried out through electronic communication and collaboration tools, it is usually difficult to sense one another's feelings and emotional states. In some cases, the distributed communication mediated by multimedia meeting systems are more effective than traditional face-to-face meetings. For example, resolving requirement conflicts in distributed-setting- structures (e.g. web-based multimedia meeting tools) can be more effective than in traditional face-to-face requirements meetings (Damian 2001).

3.2.4 Lingual distance

Lingual distance determines the level of difficulty for a heterogeneous group of people to share meanings and understanding. Lingual distance brings diversity and impedes interaction among collaboration stakeholders. However, while lingual distance often creates feelings of isolation, discouragement from collaborating, or difficulty in establishing relationships and mutual understanding, it may also foster more creative ideas due to the higher level of diversity (Pallot 2011).

3.2.5 Cognitive distance

Cognition is related to a broad range of mental activity, including proprioception, perception, sense making, categorization, inference, value judgments, emotions, and feelings, which all build on each other (Nooteboom et al. 2007). Cognitive distance refers to the differences in how people interpret, understand, and evaluate the world (Nooteboom et al. 2007; Nooteboom 1992). For organizations and teams to achieve a common purpose, people do not necessarily have to have similar knowledge or agree on personal goals, but they need to share certain basic perceptions and values to sufficiently align their competencies and motives (Nooteboom et al. 2007). Cognitive distance has a positive effect on learning by interaction, because when people with different knowledge and perspectives communicate, they help each other to stretch their knowledge for the purpose of bridging and connecting diverse knowledge (Nooteboom 1992; Nooteboom 1999). However, if cognitive distance between interaction stakeholders becomes too large, the gap in mutual understanding hinders interaction and impedes the learning process (Pennington 2008). Ideally, multidisciplinary teams should contain stakeholders with sufficient cognitive distance to share something new, but not so distant as to preclude mutual understanding (Nooteboom et al. 2007).

3.3 Technical dimension

The technical dimension comprises five distance types: conceptual, contextual, referential, semantic, and technological. For the technical dimension, the lack of common description and the lack of meaning have been found to have the most significant impact on collaboration performance (Pallot et al. 2010). The lack of common description refers to the concept of shared knowledge and the lack of meaning to the concept of sense-making; together they form the basis for reaching a mutual understanding (Pallot et al. 2010).

3.3.1 Conceptual distance

Today's design communities increasingly comprise individuals who have unique experiences, varying interests, and different perspectives about problems, and who use different knowledge systems in their work. In such heterogeneous communities, reaching a mutual understanding is challenging and usually requires an interaction and synthesis of several separate knowledge systems. In the communication of multidisciplinary collaboration, two conceptual dimensions can be identified: the expertise gap between experts and novices within a particular domain, and the conceptual gap between stakeholders from different practices or disciplines (Fischer 2004).

Conceptual distance represents the closeness in meaning among concepts, taking as reference a structured hierarchical network (Agirre and Rigau 1995). Conceptual distance between two concepts is defined in Rada et al. (1989) as the length of the shortest path that connects the concepts in a hierarchical semantic network. Effective cross-disciplinary collaboration, including individuals representing diverse perspectives and interests, requires the creation of an environment conducive to collaboration by enabling participant interactions that lead to a shared vision, through construction of a collective conceptual model (Pennington 2008; Nicolson et al. 2002). The conceptual model can be based on ontologies, for example, that formally specify concepts and relationships between concepts within a domain (Osterwalder 2004).

3.3.2 Contextual distance

Context can be defined as any information that can be used to characterize the situation of an entity where an entity is a person, a place, or an object that is considered relevant to the interaction between a user and an application, including the user and application themselves (Abowd et al. 1999). Furthermore, contextual distance results from the differences in the context of two comparable situations. Contextual factors often dictate how people perform on different tasks (Demetriadis et al. 2005). A typical example is the difference in context between an educational setting where learning takes place and a real-world situation where knowledge is applied. A student's inability to efficiently recall and use relevant knowledge in the different application context may result in poor performance (Demetriadis et al. 2005). In some cases, information technology is able to bridge contextual distance (Demetriadis et al. 2005). Context-aware computing provides domain-specific assistance that is optimized to the user situation offering the best possible content/service in the most suitable format, with respect to the activity in which the user is currently engaged (Ovaska et al. 2011).

3.3.3 Referential distance

Referential distance corresponds to the distance between the point of origin and the correlating document, measured by the number of necessary references. In this way, it is possible to describe the potential relevance of a document compared to the origin of referencing. If the referential distance increases, the relevance can be expected to decrease (Fuchs-Kittowski and Köhler 2005).

3.3.4 Semantic distance

Like semantic similarity or semantic relatedness, semantic distance refers to the distance between nodes in a hierarchical network - the shorter the path from one node to another, the more similar they are (Resnik 1995). Semantic relatedness can also be expressed by a number from -1 to 1, or between 0 and 1, where 1 represents high relatedness and 0 represents none (Pallot 2011). Semantic distance resembles conceptual distance in many ways. The difference between semantic level and conceptual level can be illustrated with a practical example, as represented by Evesti et al. (2013): "The semantic level contains separated pieces of information, e.g. temperature is minus five or a password length is seven characters. In contrast, the conceptual level makes it possible to deduct the causes of the semantic information, e.g., water will freeze or the authentication level is low". In other words, the abstraction level of knowledge is higher in conceptual level. The semantic distance between terms and words can be expressed with ontologies by tracking nodes and edges in graph representations (Norman and Hutchins 1988).

3.3.5 Technological distance

Technological distance is the result of the differences between the use of various technologies, which could be either ICT or production technologies, or even a combination of other technology types (e.g. biology) (Pallot 2011). Technological distance is also related to the ability of an organization to take advantage of the public knowledge created by another organization (Peretto and Smulders 2002). Various collaboration activities are supported by information and communication technologies that make it possible to cooperate in a distributed mode (Kotlarsky and Oshri 2005). While collaborative technologies enable remote colleagues to connect and communicate, they do not resolve the challenge of tacit knowledge, which is considered to be essential to innovative activities but is difficult to transfer without face-to-face interaction (Kogut and Zander 1992; Nonaka et al. 2000). Technological distance refers to the inability of individuals to learn from one another due the gap in technological knowledge (Pallot 2011). A lower technological distance (nearness) among collaboration stakeholders facilitates the acquisition and development of technological knowledge and technologies (Knoben and Oerlemans 2006). Thus, technological distance is affected by absorptive capacity, which determines the ability to learn and apply external knowledge (Knoben and Oerlemans 2006; Cohen and Levinthal 1990).

3.4 Legal dimension

Collaboration work can be affected by conflict situations caused by social implications, exploitation objectives, security, and confidentiality agreements, as well as privacy and inclusion concerns among stakeholders (Pallot 2011). Hence, legal and ethical aspects should not be neglected. Social implications are usually related to either trust building and mutual confidence among stakeholders, and/or public and management recognition, such as reward mechanisms, as well as learning, pre-emptive protection, control, and enabling commercial production of the outcome (Pallot 2011: Sawhney 2002). In general, wrongly addressed legal and ethical distance factors can turn any collaboration into a very low performance (Pallot 2011). In particular, an unbalanced IPR approach (collaborating partners have different approaches and objectives for ownership) seems to have a significant influence on the success of collaboration work (Pallot et al. 2010). The legal dimension includes three distance types, which are ownership, financial, and contractual.

3.4.1 Ownership distance

Intellectual property rights (IPR) determine the way in which a new innovation is accessible by its target communities and producers (Sawhney 2002). In recent scientific research, different people have had diversified opinions on how research results should be protected: some promote greater commercialization of research through formal IPR mechanisms such as patents and copyrights, while others promote greater openness through open source initiatives, for example (Sawhney 2002). In the case of software development, open source means that the intellectual property rights to software code are deposited in the public domain, and hence the code can be used and changed without requiring a user fee, such as the purchase of a licence (Kogut and Metiu 2001). Open source solutions provide small organizations with low-cost entry to product development, and also to such service business as consultancy and systems integration, for example (Karjalainen 2010).

3.4.2 Financial distance

The unbalanced amount of investments made in a relationship constitutes the basis of financial distance. The participation of each collaboration member can be considered as an asset, and if a member does not participate in the venture, the asset may not be productive. Often, financial investment behaviour is affected by past collaboration experiences and confidence, in that there is no financial investment gap or distance with other partners (Pallot 2011).

3.4.3 Contractual distance

Contractual distance is related to the specification of collaboration stakeholders' rights and obligations within different circumstances, which may occur during a collaboration project (Grossman and Hart 1986). Usually, it is impossible to foresee all possible events or incidents that may happen during collaboration, and hence many factors, often related to IPR, security, or confidentiality, are not correctly addressed in contracts (Pallot 2011; Hart and Moore 1990). The preceding aspects create contractual distance among stakeholders and may affect collaboration performance (Pallot 2011).

4. A review of existing tools supporting smart space development and management

Several approaches that are designed to provide support for smart space development and management have been delivered by research community over the years. However, it is common to the existing tools that they are usually quite technical and provide, for example, API-level support for smart space developers. Hence, the existing approaches typically require technical expertise for their use, which could make it impossible for non-technical stakeholders (domain experts, managers, etc.) to participate in the development and management of smart spaces or even to understand the different activities involved in the process. Moreover, the approaches rarely provide direct support for multidisciplinary collaboration activities or geographically distributed cooperation.

In the following sub-chapters a representative selection of existing approaches is described in more detail. A more thorough analysis of available approaches can be found from the publications included in this dissertation. The here-described approaches can be divided into two categories: approaches that aim to provide more holistic support for smart space development and management, and approaches that concentrate solely on supporting smart space application development. In Table 1, a selection of existing approaches that belong in the former category is presented. The approaches are represented using dimensions that describe the most important features of the approaches. The four dimensions specified in the table are domain, objectives, features/services provided, and data modelling.

Table 1. A review of the existing smart space development and management support approaches

Domain	**Objectives**	**Features/services provided**	**Data modelling**
'Smart Platform' (Xie et al. 2002) is a software infrastructure for smart spaces that comprise a runtime environment and a set of specification and development tools.	To provide software infrastructure for smart spaces that improves usability, features a loose-coupling structure, and provides a set of user-friendly deployment and development tools.	Publish-and-subscribe model, automatic participation in the runtime environment, agent-dependency management and resolution, debugging facilities, and an agent development kit	XML-based messaging schema.
The 'Gator Tech Smart House' (Helal et al. 2005) is a programmable pervasive space in which a smart space exists as both a runtime environment and a software library.	To enable domain experts (for example, health professionals) to develop and deploy powerful new applications for users and to offer a programmable space specifically designed for the elderly and disabled.	The generic reference architecture that is applicable to any pervasive computing space offers features for context management, context awareness, and service discovery and composition, for example.	Defines ontologies for describing various services and appliances and devices connected to the system.
'UMONS' (Lee et al. 2009) is a ubiquitous monitoring system for smart spaces.	To enable the monitoring of various ubiquitous objects and their collaborative status. To support the acquisition and processing of context data in real time, and to infer high-level status using collected raw data from ubiquitous objects. To promote awareness of current functions and the performance of services.	For example, adding/deleting of objects, agent registration, recognition of system and application errors, context data aggregation/filtering and storing in a database, a decision engine, and resource monitoring, module information and event viewers.	No specified context data modelling procedures, except a packet format for sensor data values.

In turn, Table 2 presents approaches that facilitate smart space application development. These approaches provide, for example, programming library level support for smart space development.

Table 2. A review of the existing smart space application development support approaches

Domain	Objectives	Features/services provided	Data modelling
The 'UbiSense smart platform' (Steggles and Gschwind 2005) comprises an infrastructure for building smart space applications	To support the development of smart space applications by addressing the key requirements for building smart spaces: accurate 3D positioning, scalable real-time performance, and development and deployment tools.	For example, 2D/3D visualizations of smart spaces to monitor spatial relationships between objects, data modelling capabilities, context simulation and visual configuration and development tools.	Defines a specific Ubisense data modelling language.
The integration tool 'SitCom2' and middleware bridge 'CHILix3' (Dimakis et al. 2008) facilitate integrated development of smart space applications that leverage perceptual components from different vendors.	To facilitate integrated application development in smart spaces by providing middleware for realizing interconnection functions based on high-level communication semantics and failure resilience mechanisms, and a 3D simulator tool that supports runtime development of context-aware applications and services.	For example, directory services through a knowledge-base server, support for scenario visualization and simulation, context modelling functions and publish–subscribe registration and event-type messaging services.	Communication between components and services is based on standardized XML messages. Context modelling ontologies are expressed in OWL.
'Semantic Space: An Infrastructure for Smart Spaces' (Wang et al. 2002) is a reusable architecture that utilizes semantic web technologies to ease smart space application development.	The infrastructure aims to support smart space developers in building applications that would otherwise be difficult to implement, by offering a programming library that lets applications access its functions while hiding the complexity of the underlying context processing.	The programming library contains the necessary functions to support the process of gathering contexts from data sources, managing contexts using a semantic knowledge base, handling application queries, and reasoning about contexts based on rules.	Uses the RDF/OWL language for context representation and modelling.

As presented in Tables 1 and 2, most of the existing tools are designed to support the development and integration of smart space applications. These application-oriented tools usually facilitate disaggregated system integration component simulation, and context aggregation. Furthermore, they are typically designed to enhance the development of certain types of applications, such as mobile and location-aware systems or speech recognition solutions. Additionally, they cover only certain stages of the smart space life-cycle, which limits the applicability of the approaches. Finally, most of the smart space application development support approaches tend to focus on the underlying sensors and devices, rather than on perceptual processing, and they provide no support for managing more complex context-acquisition scenarios, for example (Dimakis et al. 2008).

The above-mentioned support tools were already published at the time the majority of the research work described in this dissertation was conducted. However, there is also a set of more recent tools that share many of the same features, but that were not included in the state-of-the-art analysis performed for the research. For example, Roalter et al. have introduced a development tool chain for creation, testing, and simulation of smart environments. The tool chain consists of middleware, simulation, visualization, and prototyping tools, and it enables, for example, testing algorithms and interaction by simulation before deployment to the real world (Roalter et al. 2011). Moreover, the 'Smart Design' system has been developed to facilitate the design of smart environments (Heidari et al. 2014). The Smart Design system aims to help end-users to experience their daily activity in a virtual environment and to understand the space reaction. Additionally, it can be used to improve communications among users and designers in the design process of smart environments. Finally, Wu and Pan have described an ontology-based and context-aware smart car monitoring framework that proposes a novel context model that can represent complex driving contexts and an improved driver behaviour model for the smart car. The framework enables, for example, the representation of relevant information for a driver, based on their location, preferences, or current activity (Wu and Pan 2013).

5. Constructs

In the design science research paradigm, questions relevant to human problems are answered via the creation of innovative artefacts. In this dissertation, artefacts to facilitate the development and management of smart spaces were constructed in an iterative creation process. In an iterative process, the development of a software system is done in increments, each increment forming of an iteration and resulting in a working system (Jalote et al. 2004). As mentioned earlier, the development work was financially supported by international research projects that divided the research work into periods. Each of the projects focused on addressing distinct research questions in the area of smart space development and management, and each project resulted in a new software artefact. The artefacts created during these projects were integrated into a larger overall system that aimed at supporting different stakeholder roles in different smart space life-cycle phases.

As mentioned above, each iteration cycle resulted in a new system version that constituted its own design artefact. The first artefacts concentrated on supporting the early phases of development, whereas the latest artefacts were designed and implemented to facilitate the monitoring and maintenance of smart spaces. In this chapter, the most important elements of the resulting artefacts implemented during different iteration cycles are described.

5.1 Context and requirements

As discussed, the domain of smart spaces is complex, engaging numerous stakeholders and techniques that need to interact with each other. Moreover, the research area is relatively new and many of the smart space owners or users do not have a clear conception about the possibilities and limitations of smart spaces. Moreover, the field is constantly evolving as new technologies and infrastructures are being developed. The artefacts represented in this dissertation have been developed during international research projects that have studied the development and management of smart spaces. The projects have included several research partners, all of whom have brought their own areas of expertise and interests to the projects. The requirements for different artefact versions are mainly derived from the objectives of the above-mentioned projects.

As described earlier, in the first phase of the research, the objective was to design and implement a tool that would provide support for smart space development by visualizing ontologies. Ontologies are central to smart spaces, as they carry the meaning. One of the most important purposes of the constructed artefact was to shorten the gap from beginner to intermediate OWL ontology reader by making OWL ontologies more interesting and concrete, and above all, easier to comprehend. The starting point for selecting the most appropriate visualization techniques was the requirement of presenting contextual information and spatial relationships effectively in the visualizations. In addition, the importance of interactive elements was highlighted, as the ability to view the data from different perspectives and from different angles enhances understanding of the data (Chen et al. 1996). The final requirement considered in the first iteration cycle was offering extensive querying possibilities, because in the already existing ontology visualization approaches, the search features were surprisingly modest.

Today, a growing amount of heterogeneous data is generated in smart spaces. Thus, there is an increased need for integration of heterogeneous data sources and for inferring new knowledge from combined information to get a comprehensive view of the space. More importantly, the generated knowledge must be presented in a form that maximizes the understanding acquired by end-users. This leads to a requirement of presenting the data in such visual form that enables the human to get insight into the data, draw conclusions, and directly interact with the data by using, for example, filtering, zooming, and linking operations. During the second iteration cycle, a new version of the artefact was created. The new artefact version included features to enable real-time monitoring of smart spaces, and semantic annotation and interpretation of sensor-based context data.

The third iteration cycle was about enhancing collaboration between different stakeholders in smart space construction operations. This objective was realized by designing and implementing features that enable semantic visualization of workflows and remote monitoring of construction tasks, including the possible anomalies that may occur during processes. Furthermore, capabilities to facilitate interaction between different stakeholders were enhanced. A final enhancement implemented during the third iteration cycle was implementing features that enable involved stakeholders to analyse the performance of monitored workflows afterwards.

During the fourth iteration cycle, a new mechanism for collecting, interpreting, and representing smart space information for different stakeholders, including facility users, maintenance workers, and owners, was created. Moreover, the ability of facility users to give feedback about the current conditions was identified as an important requirement. The iteration cycle also included integrating a semantic database into the system and developing a graphical user interface for a tablet computer that allows users to examine the visualized facility information and interact with the created artefact. In order to test whether the developed features are able to meet the requirements of real-world challenges, the artefact was tested in an experiment in which it was applied in the Tervaväylä School, located in Oulu, Finland. The experiment showed that the developed components, as well as the utilized semantic techniques, are adequate in terms of performance and scalability in real-world smart space management activities.

5.2 Design and implementation

Based on the context and requirements discussed previously, artefacts that support different stakeholders throughout the smart space life-cycle were constructed. In this chapter, the main building blocks that apply to all the constructed artefacts are represented. More detailed architecture definitions can be found in the original publications.

All of the artefacts consist of four main components: Data Collection, Data Analysis and Storage, Ontology, and Data Representation. The main components are represented in Figure 5, which also contains an additional Middleware Approach component. The purpose of the Middleware Approach component is to realize interactions between the constructed approaches and external applications. In the following, the main components are described in more detail.

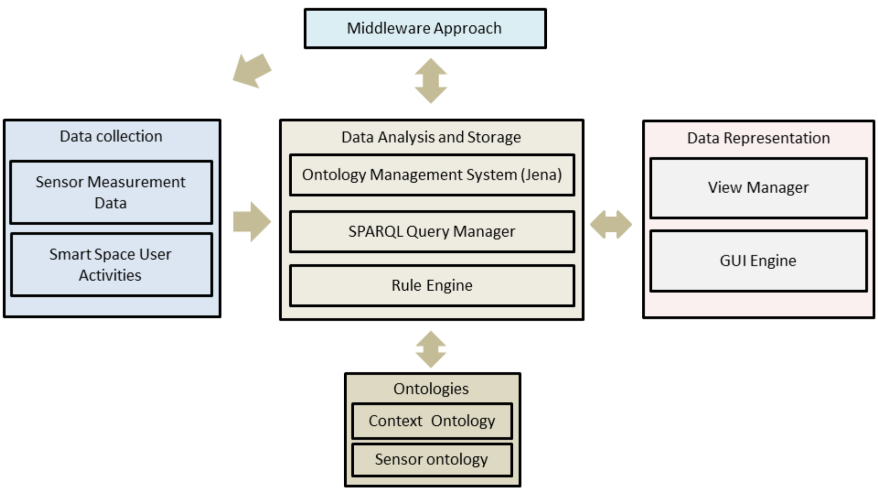

Figure 5. The main building blocks of the constructed approach

The **Data Collection** component is responsible for acquiring smart space related data. This data can be, for example, sensor-based measurement data, data about usage of electrical appliances, or data provided by external applications. The Data Collection component interacts with the Middleware Approach component, which provides data from external applications. Furthermore, the Data Collection component provides data for the Data Analysis and Storage component, which interprets and manages the collected data.

The **Data Analysis and Storage** component semantically annotates and stores different smart space related data. It enables, for example, interpretation of sensor-based unstructured measurement data into more meaningful context information. Additionally, it realizes querying functions and provides necessary information for creating visualization views. The Data Analysis and Storage component contains three sub-components: Ontology Management System, SPARQL Query Manager, and Rule Engine. The Ontology Management System sub-component utilizes a Jena (Carroll et al. 2004) programming API to process semantic data. It provides functions, for example, to acquire and update data contained by semantic models. The SPARQL Query Manager sub-component enables querying of semantically described context data. Moreover, the component interprets received query results and translates them into a form understood by the other components. The Rule Engine sub-component controls the sending of context change events to external applications.

The Data Analysis and Storage component is closely dependent on the **Ontologies** component. In the constructed artefacts, ontologies are utilized to formally represent domain-specific concepts and their relationships, and metadata that enables the system to better understand and reason about the structure and purpose of the data. Different ontologies defined for the artefacts fall into two categories: context ontologies and sensor ontologies. The context ontologies define the contextual elements and the relations among them, whereas the sensor ontologies enable the semantic modelling and storage of sensor-based measurement data.

The **Data Representation** component implements different visualization views and manages interaction between users and the system. The approach utilizes different visualization techniques in order to serve diversified end-user objectives. For example, a 2D ‘ground plan’ view enables more accurate editing operations, whereas an isometric 2,5D view offers a better general view of a smart space. Besides showing physical environments, views for representing workflows and rule information are also provided. The data that is used to build up different visualizations are acquired from the Data Analysis and Storage component. The GUI Engine component implements the interaction between visualization views and end-users by transmitting user inputs and requests to be processed by the Data Analysis and Storage component.

5.3 Visualizations and user interaction

As earlier concluded, an important objective of the constructed artefacts is to enhance mutual understanding between different smart space stakeholders. In different phases of the smart space life-cycle, large amounts of data are produced. Although semantic technologies provide efficient means for managing large amounts of data provided by heterogeneous sources, they also bring complexity, especially for stakeholders with less experience of semantics (Tane et al. 2004). However, in order to be able to contribute to the development and management process, including development, construction, and operation of smart spaces, a stakeholder must be able to explore, comprehend, and apply semantically described context data. Therefore, there is an urgent need to make this data more concrete and easier to comprehend.

Information visualization enables people to deal with complex and extensive information by taking advantage of our innate visual perception capabilities (Geisler 1998). Visualization links the two most powerful information processing tools known - the human mind and the modem computer. Visualization is a process in which data, information, and knowledge are transformed into a visual form, exploiting people's natural strengths in rapid visual pattern recognition (Gershon et al. 1998). Effective visual interfaces enable us to observe, manipulate, search, navigate, explore, filter, discover, understand, and interact with data far more rapidly and far more effectively, to discover hidden patterns and come up with new hypotheses (Keim 2001). The purpose of this chapter is to represent different visualization methods and techniques that were applied in order to enhance the understanding of smart space data.

The visualization of semantic models describing different kinds of smart spaces is beneficial throughout the life-cycle of smart spaces. During the development phase, the visualizations facilitate the creation of semantic models that simulate virtual or existing environments. Additionally, interactive visualization enables the simulation of different kinds of changes or anomalies that may occur in a context. Furthermore, during the operational phase, the visualization of context models enhances monitoring tasks by enabling the remotely examination of the overall state of a space. Effective information visualization also requires that, besides just providing an overview of the data, users should be able to zoom and filter, and obtain details on demand (Shneiderman 1996).

Figure 6 represents a screenshot from a constructed artefact in which a 2D ground plan view is shown. This view enables the creation or editing of context models through multiple drag-and-drop and drawing operations. In general, 2D views are considered better for navigating and measuring distances precisely, establishing precise relationships and performing spatial positioning (Tory et al. 2006; St. John et al. 2001).

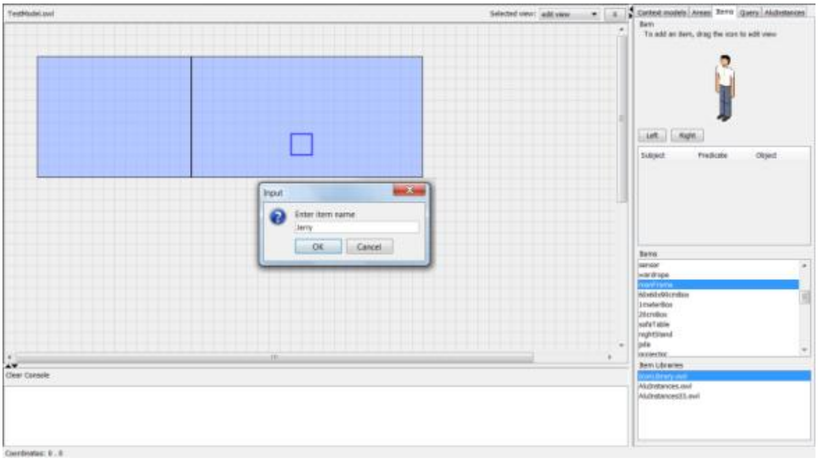

Figure 6. The edit view

Whereas 2D views have been discovered to be effective for navigating and performing spatial positioning, isometric projection has been stated to provide a general view of a space at a glance (Fernández-Vara et al. 2007). Isometric visualization has evolved during the course of this study, as is shown in Figure 7. In the left side of the figure, the isometric view after the first iteration cycle is presented. The right side of the figure represents the isometric view after the fourth iteration cycle.

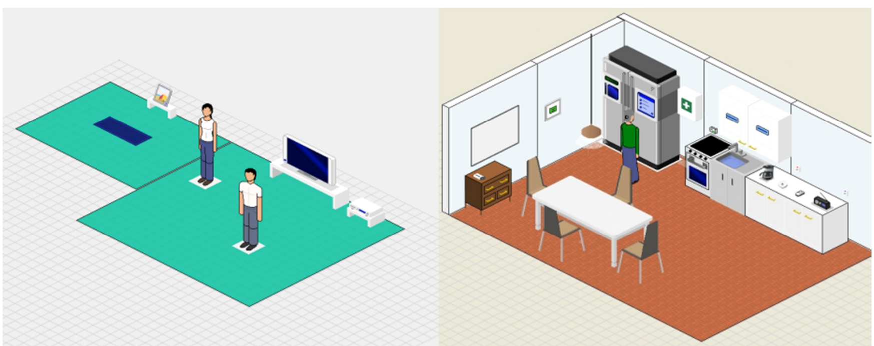

Figure 7. The evolution of isometric views

As mentioned, effective information visualization requires that users are able to obtain details on demand. During the research process conducted for this dissertation, it was discovered that, in some cases, the provided context visualizations or querying possibilities do not offer enough information for users, and hence more detailed visualizations need to be implemented. For example, semantic rules that guide the behaviour of smart spaces in different situations, or that determine when data about simulated contexts' change events are sent, were perceived as too difficult to understand for many users. Figure 8 represents a visualization in which the rule "IF a fridge door is left open THEN send an SMS message to Mike" is being graphically shown.

Figure 8. An example rule visualization

As discussed, in smart spaces workflows are often used to guide the user through different tasks. For example, in construction tasks, workflows can be used to divide complex assignments into a sequence of smaller, more manageable steps. The remote monitoring of workflow execution enhances cooperation between operators who perform various construction and maintenance tasks, and supporting personnel who provide guidance for recovery in anomalous situations. Therefore, visualizations and functions that support workflow monitoring were implemented during the third iteration cycle. The workflow monitoring features enable users to examine an up-to-date representation of the current state of a construction or maintenance process, thus facilitating common understanding among different stakeholders. Additionally, the constructed approach provides communication features that enable stakeholders to communicate with each other and form a consensus about the current situation. A screenshot representing a workflow monitoring visualization is represented in Figure 9. As can be seen, two views with differing levels of detail are provided. The offered communication functions are shown below the views.

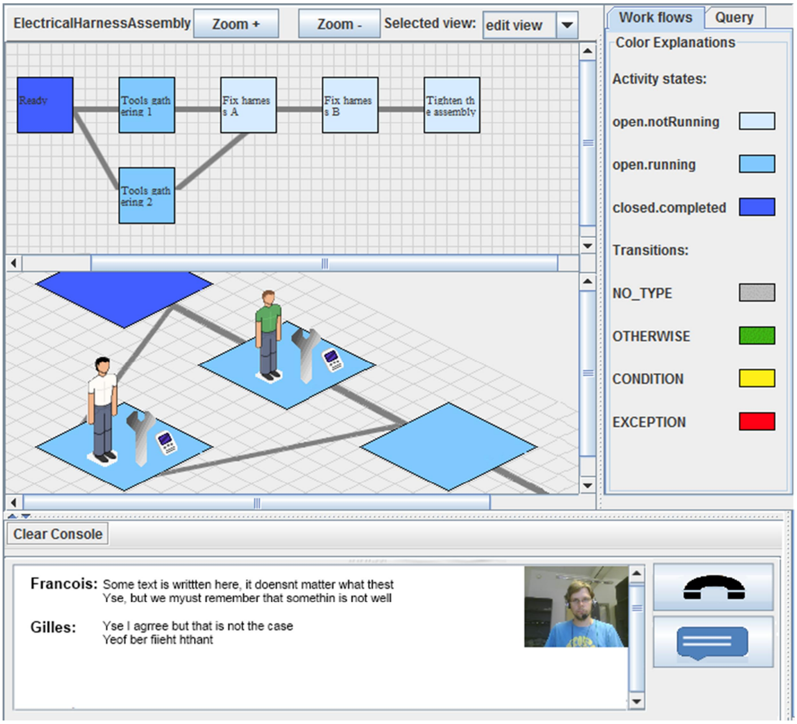

Figure 9. The monitoring of workflows

To conclude, the purpose of the different visualizations provided is to comprehensively support different stakeholders throughout the life-cycle of smart spaces. The visualizations facilitate the exploration of complex smart space information and enhance the mutual understanding among different stakeholders. Additionally, the provided interaction features enable users to examine information from different perspectives and thus understand it better. Finally, the offered communication features facilitate interaction and collaboration among stakeholders.

6. Summary of publications

The purpose of this chapter is to introduce the scientific research carried out in the enclosed papers. They introduce new innovations for supporting multidisciplinary collaborative work in the domain of smart spaces. There are a total of 5 papers enclosed, and their topics are the following:

1. An Interactive Ontology Visualization Approach for the Networked Home Environment
2. Towards a Better Understanding of Semantic Ontology-based Home Service Modelling
3. Ontology-driven data mining and information visualization for the networked home
4. Monitoring and Visualisation Approach for Collaboration Production Line Environments: A Case Study in Aircraft Assembly
5. Towards Semantic Facility Data Management

Each of the papers listed analyses the research problem from its own perspective and proposes a solution to the research problem considered in the appropriate publication. The publications can be divided into parallel and partially overlapping topics, where the overall research problem has been analysed within its particular focus area.

The first two papers focus on providing support for developers in the design phase of smart spaces. Moreover, the papers describe Artefact 1, which was constructed during the first phases of this research work. The first paper concentrates on facilitating the use of semantic technologies and ontologies through visualization. It discusses the problem of how ontologies can be visualized, particularly in the domain of smart spaces, and how interactive visualization elements can be included in the visualization.

Publication two focuses on improving understanding and discovery of semantically described services hosted by physical devices deployed in smart environments. The paper describes the abilities of the Artefact 2 to support the developers of intelligent pervasive applications that use semantic information, and also researchers who are domain experts but not yet knowledgeable in working with ontology languages and tools.

The two following papers focus more on the operational and maintenance phases of smart spaces. Moreover, they propose solutions that are targeted at end-users whose objective is not to gain more understanding of semantic technologies, but who are more interested in utilizing non-technical representations of semantic information in their work.

The objective of Publication 3 is to discuss further the technological prerequisites of enabling aggregation of heterogeneous and unstructured context data collected from multiple sources. Additionally, it analyses the application of semantic data mining techniques in realizing smart space monitoring, which enables different stakeholders to understand the intelligence embedded in the environment and supervise the space. The publication also introduces Artefact 3, which addresses some of the challenges related to smart space monitoring.

Publication 4 introduces industrial production lines as a special case of smart spaces that include various teams with different areas of technical expertise performing synchronous activities that are not always sequential. Artefact 4, which was developed to provide support for this kind of collaborative work, is also described in this paper. The paper concentrates on a use case in which cooperative work in an aeronautical final assembly line is performed.

The focus in Publication 5 is on the semantic management of facility-related information collected from heterogeneous data sources. The paper describes Artefact 5, which improves user awareness and engages facility users in the facility management process by enabling them to view the current indoor conditions and give feedback about the conditions of a building. In Addition, the artefact supports facility maintenance workers by presenting fine-grained information about facilities and enabling to interact with the facility users.

As explained earlier, this work utilizes the design science research paradigm and is carried out as an iterative process. The result of each of iteration is a research artefact that contributes to the overall research work. The constructed artefacts are verified through evaluations that provide understanding of which techniques or methods are more effective, and why certain approaches fail. The artefacts, as well as the knowledge gained from evaluations, are reported in scientific articles that are published in different conferences or journals in order to disseminate the research results to a wider audience. The proceeding of the overall research work, as well as the intermediate research results produced by the iterative research process, is presented in Figure 10.

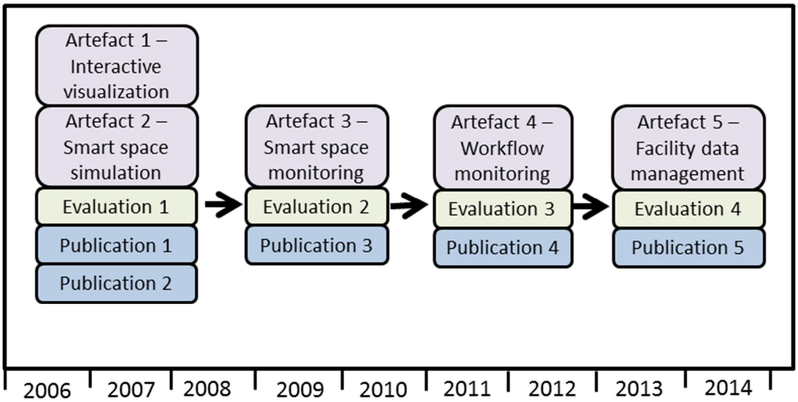

Figure 10. Workflow of research work carried out

The new innovations in the papers are further discussed in the following paragraphs. The main new findings in each publication are underlined.

6.1 Publication 1

The journal paper "An Interactive Ontology Visualization Approach for the Networked Home Environment" was published in the International journal of computer and information science and engineering, volume 1, 2007. The paper focuses on discussing the use of semantic technologies and ontologies in the domain of smart spaces. Working with ontologies and the OWL language is often perceived as complex. Looking at an OWL ontology for the first time can be overwhelming, and the gap from beginner to intermediate OWL ontology reader is cumbersome. The research problem of the publication is what kind of special requirements the domain sets for effective visualization of semantically described data, how context information should be presented and managed in the visualization, and how interaction should be implemented and managed. The artefact that is constructed to address the research problems is able to interactively visualize ontologies, particularly in the domain of smart home environments. The artefact visualizes ontologies in a domain-specific way, exploiting such representation techniques that are particularly effective at showing the physical elements of smart home environments, and spatial relationships between entities. Furthermore, the artefact provides extensive interaction possibilities that enable users to graphically create their own semantic models from scratch and extract any information from the visualized model by using SPARQL queries. The artefact aims to help people who are not familiar with ontologies and the OWL language by visualizing ontologies realistically and making OWL ontologies more concrete and easier to comprehend. The author is the main writer and innovator of the publication. The author also contributed, with Mr Toni Piirainen, to ontology development, and design and implementation of the artefact. Lic.Tech. Julia Kantorovitch and Mr. Jarmo Kalaoja contributed to the background research on the state of the art in the publication and provided technical expertise.

6.2 Publication 2

The paper "Towards a Better Understanding of Semantic Ontology-based Home Service modelling" was published in the 22nd International Conference on Advanced Information Networking and Applications, which was held in GinoWan, Okinawa, Japan, March 25–28, 2008. The research focus in the paper is on facilitating service modelling using semantic knowledge sources. Because of the complexity of ontologies, application developers find system design and application and service modelling using semantic knowledge sources, and the available service semantic description languages, to be a time and effort-consuming process. Therefore, tools are required for the adoption of semantic technologies, in particular semantic web services and also validation of service developers' proof-of concepts and developments. The solution proposed in the paper is targeted at supporting the developers of intelligent pervasive applications that use semantic information, and also researchers who are domain experts but not yet knowledgeable in working with ontology languages and tools. The artefact expands the capabilities of the artefact represented in the previous publication by enabling the semantic modelling and interactive simulation not only of physical real-world spaces and devices, but also of services, functional capabilities of services, and such conceptual contextual environments of interest as business boundaries, for example. Moreover, it supports application design by allowing verification of a service composition logic and semantic service discovery conceptually against one or more contextual scenarios. Lic.Tech. Julia Kantorovitch is the main writer of the publication. The author contributed to innovation and technical implementation of the functions needed for service modelling, context modelling, and scenario creation. Mr. Toni Piirainen contributed to the implementation of the artefact, as well as creation of the visualizations provided by the artefact. Mr. Jarmo Kalaoja contributed by generating the example simulation scenario presented in the publication and providing his expertise on service composition.

6.3 Publication 3

The paper "Ontology-driven data mining and information visualization for the networked home" was published in The Fourth International Conference on Research Challenges in Information Science held in Nice, France, May 19–21, 2010. The paper focused on researching the use of semantic technologies in extracting meaningful information from unstructured data collected from heterogeneous data sources in a smart space. The paper also discusses the appropriate semantic data mining and visualization techniques in the domain of smart spaces. The artefact proposed in the paper is modified to support the integration and visualization of sensor-based performance data that is collected from smart spaces. In order to facilitate further data mining and data integration, the earlier defined context ontology is expanded to include more sophisticated definitions of sensor properties and measurement values, user profiles and preferences, and services that are deployed in smart spaces. Additionally, the paper includes use-case scenarios that demonstrate the extraction of meaningful context information from unstructured sensor data, and performing dynamic smart space visualization and monitoring. The author is the main writer of the publication. Additionally, his contributions to the paper are the design and implementation of the visualizations and the realization of data extraction, modelling, and analysis techniques. Lic.Tech. Julia Kantorovitch contributed to the state-of-the-art research part of the publication and provided valuable ideas and expertise.

6.4 Publication 4

The journal paper "Monitoring and Visualisation Approach for Collaboration Production-Line Environments: A Case Study in Aircraft Assembly" was published in the International Journal on Human Computer Interaction, volume 3, 2012. The research problem of the publication is to present a solution that support cooperative work in an aeronautical final assembly line. In such assembly lines, the process is often not sequential: several stakeholders can be involved at the assembly station, including operators, support teams, and managers, for example. The paper introduces a use-case scenario in which two operators have received a work order to tighten two electric harnesses on an aircraft panel. Both operators work simultaneously on the same work order, which may contain several subtasks. The scenario also includes a support team that monitors the assembly procedure remotely and reacts in case of unexpected events during the process, and a station manager who is in charge of the overall organisation of the assembly line. The solution for the research problem is a semantic monitoring and visualization tool that supports cooperation between different actors in the scenario. The artefact provides better understanding of work processes by representing up-to-date visualizations of the assembly process and possible anomalies that may occur during workflow execution, and helps the support team to react more efficiently to the problems. Moreover, the artefact serves as a collaborative tool to exchange information between operators and the support team when resolving anomalies. Finally, the artefact can be utilized in the subsequent diagnosis, in which the support team and the station manager analyse the workflow performance data and any possible anomalies in cooperation. The author is the main writer and innovator of the publication. The author was also responsible for the design and implementation of the semantic monitoring and visualization tool, as well as realization of the semantic workflow data model. Lic.Tech. Julia Kantorovitch was the second innovator of the publication and also contributed to the evaluation of the artefact. Mr.

Jerome Golenzer contributed as a domain expert, providing valuable insights into the field of aircraft assembly.

6.5 Publication 5

The paper “Towards Semantic Facility Data Management” was published in the proceedings of The Third International Conference on Intelligent Systems and Applications 2014. The focus of the paper is semantically modelling and storing facility-related information collected from heterogeneous data sources. By utilizing semantic data processing mechanisms with the unstructured facility data, a more holistic view of a building’s condition (e.g. energy efficiency, indoor environment, maintenance and repair) can be created. Additionally, the semantic information was utilized by a web UI that was implemented to improve user awareness and engage facility users in the facility management process by enabling them to view the current indoor conditions and give feedback about the conditions of a building. A slightly modified version of the UI also served facility maintenance workers, as they were able to examine fine-grained information about facilities and to access the feedback provided by users and to interact with the facility users. The semantic facility data management approach was tested in an experiment, in which the system was applied in a school building environment. The results of the experiment indicate that the approach has the potential to improve the customer experience of facility users. Furthermore, by using the approach, facility maintenance workers can better adjust facility conditions according to the needs of the users and be aware of users’ perceived satisfaction and ability to work. Finally, semantic techniques were found to be adequate in terms of performance and scalability in real-world facility data management activities.

The author is the main writer of the publication. He also participated in the facility data management approach design and development work, and analysed the results of the experiment. Lic.Tech. Anu Purhonen contributed to the concept innovation and evaluation of the approach. Mr. Jarkko Kuusijärvi contributed to the design and implementation work of the approach and provided technical input for the publication. Mr. Esa Halmetoja contributed as a domain expert, providing valuable insights in the field of facility management.

7. Evaluation

In a traditional design process, designers first find a suitable and interesting problem to solve, second come up with design solutions that are developed into artefacts, and finally evaluate the constructed artefact for efficiency, utility, or performance (Hevner and Chatterjee 2010). The importance of rigorous evaluation is highlighted in the design science research process, where it requires careful definition of appropriate metrics and possibly the gathering and analysis of appropriate data (Hevner and Chatterjee 2010). Especially in the field of information systems, the evaluation of an artefact is rather complex. Information system artefacts can be evaluated in terms of function, completeness, consistency, accuracy, performance, reliability, usability, fit with the organization, and other relevant quality attributes (von Alan et al. 2004). Moreover, it must be decided whether the evaluation focus is on measuring the performance of the system (technical), or its overall usefulness to the end-user (socio-technical), or both (Hevner and Chatterjee 2010)? The technical aspect may encompass such techniques as analytical modelling, simulation, or actual measurements, whereas the socio-technical aspect can include conducting studies using quantitative surveys or qualitative interviews (Hevner and Chatterjee 2010).

In the development of such software-intensive systems as smart spaces, different stakeholders may have inconsistent, contradictory, and only partially understood objectives for behaviours and properties (e.g. performance, reliability, security, usability, and sustainability). Similarly, when a software-intensive system is being evaluated, different stakeholders often have different perspectives on what constitutes desirable outcomes. Moreover, stakeholders may look at the same thing from different viewpoints. Hence, it is important to recognize and consider the diverse perspectives of different stakeholders when evaluation procedures are being designed, and additionally, when test results are being analysed afterwards (Hevner and Chatterjee 2010).

As discussed above, in the selection of the most suitable evaluation techniques for a certain design artefact, the objectives of the evaluation, as well as the nature of the artefact, should be considered. A well-proven technique for evaluating artefacts resulting especially from design science projects is utilizing focus groups that are used as alternative to other qualitative evaluation methods, such as interviews and participant observation (Gibbs 1997). A focus group is a moderated discussion among 6–12 people, who discuss a topic under the direction of a moderator, whose role is to promote interaction and keep the discussion on the topic of interest (Gibbs 1997). The participants should be familiar with the application environment and potential users of the proposed artefact (Hevner and Chatterjee 2010).

In design science, two general forms of artefact evaluation are performed – the evaluation of the artefact to refine its design in the design science build/evaluate cycle, and the field testing of the released artefact in the application environment (Hevner 2007). Respectively, two types of focus groups can be identified in design science: *exploratory focus groups* (EFGs) study the artefact, to propose improvements in the design, continuing the cycle of build and evaluate until the artefact is released for field testing in the application environment; and *confirmatory focus groups* (CFGs), which are employed in field testing to establish the utility of the artefact in field use (Hevner and Chatterjee 2010). When properly used, the focus group is a highly relevant and rigorous approach for improving and evaluating design artefacts (Hevner and Chatterjee 2010).

As discussed in Chapter 1.4 (see Figure 1), the research presented in this dissertation has followed the design science paradigm, in which a smart space support system has been incrementally developed by firstly designing and implementing an artefact, secondly evaluating it, and thirdly utilizing the gained experiments and knowledge in the subsequent iteration cycles. Different evaluations carried out have been performed using mainly qualitative and empirical evaluation methods. The emphases on the evaluations have been on trying to find out how well the constructed artefacts address the issues raised in the research questions. For example, each of the evaluations focused on different phases of the smart space life-cycle. Additionally, through questionnaires, end-user interviews, and observations, the ability of the chosen visualization techniques to enhance the understanding of smart spaces and semantic technologies was clarified. Table 3 represents the different iteration cycles performed, including constructed artefacts, written publications, and used evaluation methods.

Table 3. Iteration cycles with resulting artefacts, written publications, and used evaluation methods

Iteration	Resulting artefact	Publica-tions	Evaluation methods
Cycle 1	Interactive visualization artefacts for domain smart spaces that supports application and service developers and domain experts Enables scenario simulations	Publication 1, Publication 2	User test, questionnaire
Cycle 2	Smart space monitoring artefact Semantic management and visualization of heterogeneous sensor-based measurement data	Publication 3	Scenario-based technique End-user interviews
Cycle 3	Artefact for monitoring workflows guiding users through construction and maintenance Enhances mutual understanding and communication between stakeholders	Publication 4	User test, questionnaire, focus group
Cycle 4	Semantic facility data management approach that enables the collection, interpretation, and representation of facility information for different stakeholders Enables examination of facility data and giving feedback	Publication 5	Usage metrics, questionnaire

As discussed earlier, in system development, different stakeholders often have different perspectives on what constitutes desirable outcomes. Thus, also in an evaluation process, the diverse perspectives of stakeholders should be recognized and considered. Table 4 represents the different stakeholder roles that were involved in the performed evaluations.

Table 4. Involved stakeholder roles in different evaluations performed

Stakeholder roles	Evaluation 1	Evaluation 2	Evaluation 3	Evaluation 4
Owner			x	
General developer	x			
Administrator		x	x	
Technician	x			
Device manufacturer				
Middleware provider				
Service provider	x			
End-user		x		x
Facility maintenance worker		x		x

7.1 Evaluation 1

The result of the first iteration cycle is described in Publication 1 and Publication 2. The two design artefacts produced by the first iteration cycle are software approaches that aim to support smart space application and service developers. The artefacts offer views of semantic context data and a graphical user interface to i) a context broker that enables, for example, acquisition, reasoning, and sharing of context knowledge, and ii) a semantic service repository that encapsulates different services. The approaches facilitate the management of the above-mentioned components in an application and service development.

Since both of the approaches produced by the first iteration cycle focus on the development phase of the smart space life-cycle and share many common goals and functionalities, the features provided by the artefacts were integrated into a single software tool and evaluated at the same time. The assessment of the integrated approach was carried out using socio-technical and qualitative evaluation technique. Test participants had to work with the tool, perform given tasks, and respond to a questionnaire afterwards. Since the tool is not an actual middleware component and does not affect the middleware efficiency at all, the ease of use, usability, user experience, and added value in smart space application and service development were considered as interesting aspects to evaluate instead of assessing, for example, the runtime or performance of the approach.

The questionnaire used a five-level grading system where five is the best and one the worst grade, with three being average. After each question, there was a possibility to add free comments, and participants did use this opportunity. The phase where the test participants worked with the approach was monitored, but the questionnaires were returned anonymously. Due to the fact that the approach was the result of the first iteration cycle, it was predicted that most of the critique would deal with shortcomings or complexity of the graphical user interface. Regardless of how the user interface follows the guidelines for usability, it was considered interesting to see how useful the participants find the features of the approach. Among others, the following questions were considered relevant for this evaluation: Is the whole idea of having such a tool worthwhile? Does it offer any help in stepping into the world of semantic context data, context sources, and service registries when developing applications for smart spaces?

The tasks that the test participants had to do included such assignments as starting up the approach, creating semantic models of smart spaces, and registering them as a context source for a middleware solution, creating their own device libraries, registering services in a semantic service repository, and testing the context source and service discovery. Participants had written instructions on how to perform the tasks, but they were not very detailed. This was to find out the problems in the usability and ease of learning of the software tool. The test participants came from various backgrounds, but all had at least some knowledge of smart spaces and/or experience of software development.

7.1.1 Results of evaluation 1

In general, the first evaluation was useful and revealed some extremely interesting points about the constructed approach and enhanced the discovery of which features users find useful and easy to use, and which parts of the application still need to be improved. The overall experience of working with the approach was considered to be positive. The graphical user interface was functional and easy to learn, at least with instructions. The technologies used in the domain of smart spaces were a bit unfamiliar for a large number of the respondents, which caused confusion. For example, the messages produced by the application were in many cases found to be too cryptic. In addition, the exact meaning of some functions and/or buttons was perceived as hard to understand for some. However, the visualizations were considered informative, enhancing the understanding of semantically described context data. The overall graphical appearance and the user interface of the approach also received positive feedback.

The test situation included various tasks. Creating new models, adding areas and items, and registering a context model as a context data source for external applications were considered to be easy tasks in general. In contrast, the building of their own devices was perceived as a complicated assignment by many of the test participants. This is probably because the adding of new devices requires editing RDF descriptions with a text editor. A number of respondents commented that there should be a graphical editor within the constructed approach to support this task, which was valuable feedback for the developer team. Finally, the adding of services was considered more difficult than the adding of context sources.

The questionnaire included questions about perceived ease-of-use and perceived usefulness of the tool. To sum up the results of the questionnaire, the constructed approach was considered to facilitate the process of creating context-aware services and applications. The time used in creating test context sources was decreased noticeably and the monitoring of the context source and service registries was found to ease the debugging. Nevertheless, many respondents still mentioned the complexity of the tool. In addition, one respondent thought that using the approach would not save much time because they would play around with it too much. The approach itself did not cause any quality issues during the evaluation. However, most respondents reported some performance issues, especially when adding new services to a context model. In a nutshell, the evaluated tool was perceived as a useful and nice-looking but slightly complex tool.

7.2 Evaluation 2

The artefact resulting from the second iteration cycle is described in Publication 3. The artefact represented in this publication acquires heterogeneous data from a smart space, extracts meaningful information from the collected unstructured data, and provides visualizations of the information, and thereby enables remote monitoring of smart spaces. The resulting software approach is intended to be used during the operational phase of the smart space life-cycle.

The evaluation of the approach was performed using a scenario-based technique. Scenario-based evaluation techniques (Carroll 2000) utilize scenarios that represent concrete instances of system use that can span space, time, people, and system features, while providing designers, developers, and other stakeholders with ecologically valid units on which to anchor their analyses (Haynes et al. 2004). It is essential for scenario-based evaluation that it is grounded in the concrete use scenarios for which the system under evaluation is intended (Carroll 2000). Scenarios are narratives that describe the details of a user interaction with a system or application (Haynes et al. 2004).

The scenario utilized in the evaluation involved a 75-year-old woman named Anna, who lives in her own apartment. Anna’s current wellness information is estimated by combining data from several data sources that are contained by Anna’s home. The system collects sensor data from wearable sensors, environment sensors, wellness self-evaluations, social proximity, and health record information, for example. The system interprets and stores the collected information in order to deduce such conclusions as how many times certain electrical appliances are used or different doors opened during the day. This information can be utilized by Anna herself, relatives, and health-care professionals.

In order to address the challenges raised by the above-described scenario, the artefact constructed in the second iteration cycle has to be able to effectively collect, semantically store, and extract meaningful information from the data provided by the environment. The semantic management of heterogeneous sensor data was selected as the most important aspect to evaluate. The evaluation was started by performing experimentations with simulated sensor data. The utilization of virtual sensors enabled the generation of context information with configured values and event models. Those models used either predefined or randomly generated values that enabled modelling the non-deterministic behaviour of physical environments. In the second phase of the evaluation, the management of real sensor data was tested with the approach. The test environment contained a bed sensor that enabled the collection of such context data as the times an elderly person has got out of the bed during the night, or the respiratory frequency of the elderly person.

7.2.1 Results of evaluation 2

The evaluation showed that the constructed artefact is able to effectively collect and semantically store different kinds of sensor measurement data. In the test scenario, the approach had to be able to manage both simulated sensor data and real-life sensor measurement data collected from Anna's bed. The processing of bed sensor data revealed some performance issues, as the bed sensors provided hundreds of events per minute. Due to the high computational resources required by semantic data processing, the bed sensor data had to be pre-processed before sensor events could be converted into a semantic form.

In the evaluation, it was also assessed how effectively the artefact is able to extract meaningful information from the collected sensor data and present it to users. By using semantic reasoning, SPARQL queries, and data visualization, the artefact enabled the creation of graphical representations that showed parts of the collected sensor data in a more comprehensible form. In this way, it was possible, for example, to produce diagrams that provided valuable information about a person's possible sleeping disorders. Some of the resulting visualizations were also assessed by health-care professionals at the Hyvä Ikä exhibition held in Tampere in October 2008. The feedback received was positive in general. In particular, the abilities to remotely monitor homes of the elderly and share information about the current state of the homes with other caregivers or relatives were considered to be useful features. However, the privacy issue that may arise as people are being monitored caused concern among the interviewed professionals.

To conclude, the evaluation showed that the constructed approach was able to semantically store different kinds of sensor data and extract meaningful information from it. Additionally, the remote monitoring of elderly homes was considered to be a useful feature that potentially facilitates the work of caregivers, enhances the collaboration between different stakeholders, and facilitates independent living. On the other hand, some concerns related to performance and ethical issues were discovered during the evaluation. These problems were thought to deserve consideration in the future development work on the artefact.

7.3 Evaluation 3

The third iteration cycle concentrated on designing and implementing features that would provide more support for the construction and maintenance work of smart spaces. In Publication 4, a real-life scenario related to aircraft assembly lines is represented. In the scenario, the objective of the artefact is to enhance cooperation between different stakeholders by enabling remote monitoring of different processes and the exchange of information through communication functions provided by the tool. The approach can also be utilized in a subsequent diagnosis, in which the performed assembly work is analysed.

The evaluation was carried out using two assessment methods: a focus group session and analytical user testing. Similarly to evaluation 1, the objective of evaluation 3 was to assess the usability and perceived usefulness of the constructed approach. Thus, a user-based evaluation, in which test subjects were asked to perform a set of tasks with the technology, was utilized. Additionally, test participants were asked to complete a post-test questionnaire that gathered quantitative and qualitative data on participant perceptions.

The evaluation was inspired by a scenario related to an aircraft assembly line, in which two operators have received a work order to tighten two electric harnesses on an aircraft panel. The electrical assembly procedure is presented from its planning to its certification, including the treatment of an unexpected event during the process. The main goal of the approach in the scenario was to enable remote monitoring of workflows that guide the operators through the process, and to facilitate communication between the different actors involved. Additionally, it had an important role in the treatment of an unexpected event that occurred during the process.

As mentioned, the emphasis of the evaluation was on measuring the usability and perceived usefulness of the approach. According to the Technology Acceptance model (Davis 1989), a number of factors influence users' decisions about how and when they will use new technology. For example, perceived usefulness that is defined as "the degree to which a person believes that using a particular system would enhance their job performance" and perceived ease-of-use that is defined as "the degree to which a person believes that using a particular system would be free from effort" are important factors determining whether people will accept or reject an emerging information technology (Davis 1989). Parts of the metric introduced by Davis (1989) to measure perceived usefulness and perceived ease-of-use of a technology were reused in the post-test questionnaire.

The focus group session was organised by inviting 7 researchers with heterogeneous experience in workflow management, semantic knowledge modelling, services, and support tools for the discussion. The discussion was led by a moderator who presented the constructed approach and the purpose and most important requirements of the tool. Once the approach was introduced to the members of the focus group, the discussion was started. The moderator steered the session by following a predefined discussion plan that contained some questions and tasks for the focus group. Time was also reserved for open discussion in order to get more spontaneous opinions and reactions from the focus group. The session was recorded by taking notes that served as material for later analysis.

The participants in analytical testing consisted of smart space application and service developers and an aeronautical domain specialist. The test participants were asked to perform tasks related to the aircraft manufacturing scenario using the constructed approach, and to complete a post-test questionnaire. The objective of the questionnaire was to measure the perceived ease-of-use and the perceived usefulness of the tool, and it contained such questions as “How easy was it to learn how to use the approach?”, “Using the system would enhance my effectiveness on the job” and “I would find the system useful in my job“. Additionally, more general questions included, for example, “Did you encounter any performance issues?” and “How would you rate your overall experience with the approach?”

7.3.1 Results of evaluation 3

Overall, the results of the evaluation were positive: most of the people that participated in the test perceived the artefact to be a useful tool with the potential to enhance effectiveness and increase the productivity of their jobs. On the other hand, the test revealed that the tool is not a finished product, but a work-in-process, and there is still a lot of room for improvement.

The evaluation was carried out in two phases: firstly a focus group session was organized, and secondly analytical user tests were performed. The focus group session gave numerous suggestions on possible directions in which the tool could be developed, and also useful feedback concerning the graphical appearance of the approach was received. The most concrete development ideas were related to the scope of use of semantic technologies and the utilization of the artefact in other problem domains. For example, many of the session participants considered that if the approach used the capabilities provided by semantic technologies more effectively, it could be more effectively utilized in the design phase of workflows. Additionally, more efficient use of semantic technologies could improve the tool’s ability to treat unexpected events, for example.

The analytical user tests provided information about the system’s ability to meet its requirements in terms of usability and usefulness. According to the test results, the approach was perceived as a useful tool by its end-users. Additionally, the chosen visualization techniques were considered to be suitable for monitoring workflows. At the same time, the user tests provided plenty of ideas on how to develop the artefact further. For example, numerous suggestions on how information about unexpected event and anomalies should be represented in visualizations were received. Furthermore, although the approach was perceived to have potential in facilitating collaboration between different actors, some of the interactive features were still considered to be deficient. For example, the communication functions provided by the tool were found to still require some improvements. The identified shortcomings were addressed in the subsequent development work.

7.4 Evaluation 4

During the fourth iteration cycle, the focus was on smart space maintenance, which was supported with a created artefact designed for facility data management. The artefact enabled, for example, collection, interpretation, and representation of facility information for different stakeholders, including facility users, maintenance workers, and owners. Besides examining visualized facility information, the approach enabled facility users to give feedback about the conditions of the building. Furthermore, the artefact aimed to aid the work of facility maintenance workers by offering a unified interface to examine building data and to interact with facility users.

The artefact was evaluated with an experiment in which the semantic facility data management artefact was applied in the Tervaväylä School, located in Oulu, Finland. Besides the created artefact, the test environment included a building automation system and a wireless sensor network that provided sensor-based measurement data, a server machine that hosted a semantic database, and a tablet computer that held a graphical user interface (GUI) that enabled users to examine visualized facility information and interact with the approach. The experiment involved field tests that were conducted in order to validate the functioning of the artefact in real-world settings, to examine the usage rate of the artefact among users, and to study the effects of the artefact on facility user satisfaction.

During the field test periods, the tablet hosting the GUI of the artefact was located in the school employees' break room, where it was available for anyone to use. In total, three separate test periods were performed, and between each period, the artefact was improved according to the user feedback received. The artefact was also introduced to the facility maintenance workers of the Tervaväylä School. The facility maintenance workers were familiarized with the artefact and they were given an opportunity to test it. Afterwards, the facility maintenance workers answered a questionnaire that measured the perceived ease-of-use and perceived usefulness.

7.4.1 Results of evaluation 4

The test results were collected by analysing the usage metrics and questionnaire answers. The usage metrics provided such information as the amount of time that a user spent using the artefact, and the number of GUI pages viewed. The questionnaire provided data related to the overall usability and perceived usefulness, for example. By analysing the results, it was ascertained which features of the tool the end-users find useful and easy to use, and which parts of the application still need improvements.

To begin with, the evaluation proved the abilities of the artefact to effectively merge and interpret heterogeneous facility data and to produce interactive visualizations for different stakeholders. Moreover, the usage metrics indicated that the users were able to utilize the artefact as it was designed to be used. Additionally, the interest towards the approach was at its peak during the first field test period, in which the different features were used most frequently. According to the questionnaire results, the visualizations offered by the artefact were considered to be an important and useful information source by facility users. Nevertheless, the usability of the approach was found to require improvements. Moreover, it was perceived as difficult to give written feedback using the tablet machine. Some data representation techniques were also regarded as difficult to understand.

According to the questionnaire answers given by facility maintenance workers, the possibility to receive feedback directly from the users of the building was considered to be a useful feature. However, the facility maintenance workers suggested that there should be some kind of filter to extract the most important service requests from the received feedback. Moreover, in general the idea of having a single interface for observing diverse facility information was appreciated. The suggestions for improvements included fine-tuning the user interface. For example, the artefact should offer more flexibility in selecting which particular aspects of the data are presented. The questionnaire answers also indicated that more advanced means to give additional information through the approach should be provided. For instance, it would be useful to inform the facility users about water or heating system outages or the testing of fire alarms. A number of the suggested improvements were addressed in the next version of the artefact.

7.5 Summary of the evaluations

The evaluation of the artefacts created over the course of this study was performed using multiple methods, which included analytical user testing, usage metrics, questionnaires, scenario-based techniques, and focus groups. The objective of the user studies and questionnaires was to measure the perceived usefulness and perceived ease-of-use of the evaluated artefacts. Additionally, by using scenario-based evaluation techniques, it was aimed to clarify how well an artefact is able to fulfil the technical requirements set for it. Finally, the utilization of focus groups gave valuable information on possible future development directions, for example.

The performed evaluations were useful and revealed some extremely interesting points about the constructed artefacts. To summarize the results, the artefacts were perceived to be useful and easy to use in general. Moreover, the artefacts were proven to satisfy a majority of the identified requirements, and the provided visualizations were considered to be informative, enhancing the understanding of semantically described data. The utilization of focus groups gave numerous suggestions on future development of the artefacts and useful feedback concerning the graphical appearance of the artefacts, for example.

The evaluations also provided information about the existing deficiencies of the artefacts. For example, some of the graphical editing operations were considered to be complicated by test participants. Furthermore, the evaluations revealed some limitations in visualizations and communication features provided by the artefacts. In addition, some concerns related to performance and ethical issues were discovered during the evaluation. The discovered deficiencies were analysed after each of the evaluations and the most important shortcomings were addressed in the subsequent development work. As a whole, the results of the performed evaluations provided valuable input and advice for the further development of the artefacts.

8. Analysis

The purpose of this dissertation is to discuss methods for supporting stakeholders in the development and operation of smart spaces. The research is conducted using the design science research paradigm, in which questions relevant to human problems are answered through the creation of innovative artefacts. The artefacts were created in scientific research projects that all concentrated on studying and developing different aspects of smart spaces. Furthermore, the aim of each of the publications is to address the needs of certain stakeholder roles. The resulting artefacts also focus on supporting different phases of the smart space life-cycle.

The emphasis of the dissertation is not only on supporting individual stakeholders, but also on facilitating the collaboration between different actors participating in smart space development and operation. The collaborative work is usually performed in multidisciplinary and geographically distributed teams, and is affected by a multitude of factors that must be taken into consideration. Thus, the collaboration distance framework that clusters various distance dimensions and related factors appearing in the course of distributed or distant collaboration was selected as one of the utilized analysis metrics. The framework provides a holistic model and increased understanding on the various distance factors affecting the collaboration mechanics and performance. Moreover, because the holistic model illustrates and explains the relationships between distance factors, collaboration barriers, distance types, collaboration tools, and distributed teams, it was considered to provide a sound basis for the analysis.

At the beginning of this chapter, each of the publications is analysed in terms of the smart space life-cycle phases they are concentrated on and the stakeholder roles for which they aim to provide support. Subsequently, the publications are analysed against the collaboration distance framework in order to gain understanding of how extensively the constructed artefacts can enhance multidisciplinary and geographically distributed cooperation work. The chapter is concluded with an analysis of how the research questions introduced in Chapter 1.2 were addressed.

8.1 Publications, smart space life-cycle phases, and stakeholder roles

Table 5 represents the life-cycle phases and involved stakeholder groups discussed in each of the publications.

Table 5. The division of life-cycle phases and involved stakeholders between different publications

Publication	Life-cycle phase	Involved stakeholders
Publication 1	Development	General developer, Administrator, Service provider
Publication 2	Development	General developer, Administrator, Service provider, End-user
Publication 3	Operational	Owner, Facility maintenance worker, End-user, Administrator
Publication 4	Construction	General developer, Administrator, Technician
Publication 5	Operational	Facility maintenance worker, End-user, Owner

The following sub-chapters describe in more detail how different life-cycle phases and stakeholder groups are supported in each of the publications included in this dissertation.

8.1.1 Publication 1

Publication 1 aims to introduce means that enhance the understanding of semantic technologies by visualizing ontologies, particularly in the domain of smart spaces. The artefact described in the publication is designed to be used in the development phase of smart spaces. More specifically, it supports the context-aware architecting in which components for facilitating knowledge creation and usage in the incremental and long-lasting development of smart spaces are created. Importantly, the context-aware architecting encompasses creating context ontologies and ontology-based context models that formally describe different entities of a space, and facilitates context-awareness. However, as discussed earlier, the creation of context ontologies and ontology-based context models is complex. Thus, there is a need for user-friendly graphical tools that make the design of ontological context models viable for developers, administrators, and service providers who are not particularly familiar with description logics (Pantsar-Syvaniemi et al. 2010).

The constructed artefact defines an example context ontology that describes the basic concepts essential for the domain of smart spaces. Involved stakeholders are able to examine the context ontology and expand it to better serve their purposes. Moreover, the artefact provides interaction features that enable stakeholders to graphically create their own ontology-based context models from scratch and extract information from the models. Additionally, it enables developers, administrators, and service providers who are not familiar with semantic techniques to participate in the collaboration work in which context-aware architecting is performed.

8.1.2 Publication 2

The objective of Publication 2 was to describe new features designed and implemented for the artefact represented in Publication 1. These new functions included, for example, better support for semantically modelling and simulating physical spaces and devices, services, and functional capabilities of services. The new artefact introduced by the Publication 2 also enabled the demonstration and verification of semantic service discovery conceptually against one or more contextual scenarios. Additionally, the artefact facilitated addressing such problems as how to find the most suitable services in different contextual situations, and how to make service composition application adaptable to the current context (e.g. persons move, new devices/services are registered).

As discussed earlier, user orientation is an obligatory feature of smart spaces. During the development phase, and more specifically scenario-based design, different patterns that are used as building blocks for adapting and configuring a generic application model for a particular usage scenario are developed. The constructed artefact supports the creation of these patterns, for example, by enabling the simulation of different kinds of usage scenarios that demonstrate service discovery and service composition in various situations. The visualization of these scenarios is intended to stimulate discussion among developers, administrators, and service providers concerning the relevance of diversified pattern ideas and suggestions. Additionally, the visualization of simulated scenarios should create mutual understanding between developers and end-users, which facilitates identifying user needs and requirements.

8.1.3 Publication 3

The artefact presented in Publication 3 aimed to provide means for smart space monitoring that is essential in the operational phase of the smart space life-cycle. The artefact acquires heterogeneous data provided by various sources, semantically annotates it, and finally extracts meaningful information from the collected data. Additionally, the artefact provides illustrative and informative visualization to the provided context information. By fusing and integrating sensed, unstructured context data, inferring high-level context information and providing comprehensive views, the artefact enables non-technically trained users to monitor smart spaces and facilitates the collaboration between, for example, smart space owners, administrators, facility maintenance workers, and end-users. Additionally, by enabling the automatic connection of a smart home system at a distance, and remotely checking the status of the monitored space, the artefact enables the involved stakeholders to be automatically informed of any malfunctions or emergency situations.

8.1.4 Publication 4

In Publication 4, the focus is on designing and developing features that would support the tasks encompassed by the construction work of smart spaces. Often, different tasks involve various teams with different areas of technical expertise, and are performed in collaborative working environments in which technicians are supported by smart space administrators or developers, whose role is to design, coordinate, and monitor the work. Additionally, characteristics of the construction work are interdependencies between different activities, heterogeneous data sources, delays in supplier components, and changes in the human resources involved.

To address the above-mentioned challenges, various construction tasks can be supported with different technologies. For example, semantic modelling of workflows that are designed to guide the performance of tasks, remote monitoring and visualisation of run-time execution of processes, and sophisticated communication systems are used for facilitating collaboration activities. In Publication 4, the capabilities of the constructed artefact to support collaboration is demonstrated with a real-life scenario related to an aircraft assembly line. In the scenario, the artefact enhances cooperation between the involved stakeholders by enabling them to remotely monitor different processes, exchange information, and perform a subsequent diagnosis.

8.1.5 Publication 5

Publication 5 discusses supporting the work of facility maintenance workers in the operational phase by integrating heterogeneous facility-related data into a knowledge base using semantic technologies, and providing interactive visualizations that enable easy access to and examination of the collected information. The artefact introduced in the publication also aims to engage facility users in the process of facility management by enabling them to view the current indoor conditions and give feedback about the conditions of the building.

According to the experiment described in Publication 5, the increased user awareness, as well as the ability to participate in the facility management process, was proven to increase user satisfaction. Moreover, the facility maintenance workers perceived that, with the ability to examine the existing or historical conditions of the building and to interact directly with facility users, they are able to better adjust the conditions to the needs of the users and to be aware of users' perceived satisfaction and ability to work.

8.2 Publications and the collaboration distance framework

The different development and management activities of smart spaces are usually performed in multidisciplinary and geographically distributed teams. Thus, an important objective of the artefacts represented in this dissertation is addressing the challenges related to collaborative work that is affected by a multitude of factors that must be taken into consideration. The collaboration distance framework that clusters various distance dimensions and related factors appearing in the course of distributed or distant collaboration was selected as one of the analysis metric to be used in this dissertation, because it provides a holistic model that compiles and discusses various distance factors affecting the collaboration mechanics and performance. The collaboration distance framework illustrates and explains the relationships between distance factors, collaboration barriers, distance types, collaboration tools, and distributed teams, hence constituting a sound basis for the analysis.

Table 6 presents the results of the analysis in which the artefacts presented in each of the publications are examined using the metric described above. In the table, the distance factors are shown on the y-axis and the publications on the x-axis. The ability of the artefacts to overcome different distance factors is indicated using weight factors that are adopted from the QFD (Govers 1996) (Quality Function Deployment) method. The factors are categorized using a three-tiered classification system that distinguishes between "strong", "moderate", and "weak", depending on how well an artefact is able to help to bridge or compress a distance factor. In the table, the different factor categorizations are indicated with the following symbols: "strong" = Δ, "moderate" = • and "weak" = o. If a distance factor is not applicable for the analysed artefact, it is indicated as "-".

Table 6. Analysis results of the artefacts represented in publications (Δ = strongly, • = "moderately", o = "weakly" and - = not applicable)

	Publication 1	Publication 2	Publication 3	Publication 4	Publication 5
Structural					
Configurational	•	o	o	•	•
Institutional	o	o	o	o	•
Organisational	o	o	o	o	o
Spatial	o	•	•	Δ	Δ
Temporal	o	•	•	•	Δ
Social					
Relational	-	-	-	o	-
Cultural	•	o	o	•	o
Emotional	-	-	o	-	-
Lingual	Δ	•	•	•	•
Cognitive	•	•	•	Δ	•
Technical					
Conceptual	Δ	Δ	•	•	Δ
Contextual	-	-	-	o	-
Referential	-	-	-	-	-
Semantic	•	•	Δ	•	•
Technological	Δ	•	Δ	Δ	•
Legal					
Ownership	Δ	Δ	Δ	Δ	Δ
Financial	-	-	-	-	-
Contractual	-	-	-	-	-

In the following, brief descriptions of the abilities of the artefacts described in the different publications to provide support for collaborative smart space development and management are presented.

The artefact introduced in Publication 1 (later referred to as 'Artefact 1') aims to support developers who are not familiar with semantic techniques to participate in the collaboration work in which context-aware architecting is performed. As mentioned earlier, context-aware architecting encompasses creating context ontologies and ontology-based context models, which are complex tasks especially for developers with little or no experience in semantic technologies. Thus, there is a need for user-friendly graphical tools that make the design of ontological context models viable for developers that are not particularly familiar with description logics (Pantsar-Syvaniemi et al. 2010). Artefact 1 addresses this need by facilitating context ontology creation and providing interaction features that enable users to graphically create their own ontology-based context models from scratch.

The artefact introduced in Publication 2 (later referred to as 'Artefact 2') improves the capabilities of Artefact 1 to support the semantic modelling and simulation of physical spaces and devices, services, and functional capabilities of services. In more detail, Artefact 2 aims to support scenario-based design and scenario-based evaluation and testing phases by facilitating the interactive simulation of physical real-world contextual environments without requiring comprehensive knowledge of ontologies. The ability to simulate and visualize contexts and scenarios is intended to stimulate discussion among developers concerning the relevance of diversified pattern ideas and suggestions. Additionally, the visualization of simulated scenarios can create mutual understanding between developers and end-users, which facilitates identifying user needs and requirements. Finally, by providing an easy-to-use and easily accessible approach for utilizing semantic context models in scenario-based testing and evaluation, Artefact 2 facilitates collaborative work between general space developers and space technicians, for example.

The artefact discussed in Publication 3 (later referred to as 'Artefact 3') aims to provide means for smart space monitoring that is essential in the operational phase of the smart space life-cycle. By collecting and integrating unstructured context data, inferring high-level context information, and providing comprehensive visualizations, the artefact enables non-technically trained users to monitor smart spaces, and facilitates the collaboration between, for example, smart space owners, developers, administrators, and end-users. Additionally, the artefact enables different stakeholders to be automatically informed of any malfunctions or emergency situations.

One characteristic of the construction activities of smart spaces is that they involve various teams with different areas of expertise and are performed in collaborative working environments in which operators or technicians are supported by smart space administrators or developers, whose role is to design, coordinate, and monitor the work. The artefact introduced in Publication 4 (later referred to as 'Artefact 4') addresses the challenges raised by smart space construction work by utilizing different technologies and methods. For instance, the semantic modelling of workflows that guide the performance of tasks facilitates the solving of interoperability problems for knowledge sharing, whereas the visualization of run-time execution of processes enhances mutual understanding between different stakeholders. Moreover, the different interaction and communication functions provided facilitate various collaboration activities.

The artefact described in Publication 5 (later referred to as 'Artefact 5') concentrates on providing support for smart space maintenance. The artefact enhances communication between smart space users and maintenance workers by providing mechanisms to inform maintenance workers about possible defects or service requests. Moreover, the artefact enables the visual examination of versatile facility information related to current or historical indoor conditions, for example. The feedback provided by smart space users and the offered facility information enable maintenance workers to better adjust the conditions to the needs of the users, and to be aware of users' perceived satisfaction and ability to work.

The following sub-chapters provide a more detailed analysis of the abilities of the artefacts to overcome the identified distance factors.

8.2.1 Analysis of configurational distance

As stated in Chapter 3.1.1, the configurational distance results from the distribution of resources, expertise, and the team members' feel of isolation, which can possibly be minimized through communication technologies that increase their sense of connectedness and involvement. Moreover, the configurational distance creates coordination complexity, for example, in terms of how power and expertise in decision-making are balanced across distributed sites. In the following paragraphs, the abilities of the artefacts that are described in the publications to bridge configurational distance is discussed in more detail.

The effortless creation of context ontologies and models enabled by Artefact 1 can bridge configurational distance, as collaboration stakeholders with less expertise or power in decision-making are able to participate in the context-aware architecting by contributing their own ideas and suggestions for different components. Furthermore, by allowing people with diverse levels of expertise to contribute to the collaboration work in which scenario-based design, evaluation, and testing is performed, Artefact 2 is able to reduce configurational distance to some extent.

Artefact 3 is able to overcome configurational distance by increasing collaboration members' awareness and knowledge of state information. However, the artefact does not provide any direct interaction features that would enable different stakeholders to communicate with each other. Thus, it can only slightly decrease team members' feelings of isolation.

Artefact 4 increases the sense of connectedness and involvement by providing communication methods and bringing awareness of activities by enabling the remote monitoring of construction and maintenance processes. Respectively, Artefact 5 has the potential to bridge configurational distance by increasing smart space users' sense of involvement through improving the possibilities to influence smart space indoor conditions and maintenance operations.

8.2.2 Analysis of Institutional distance

In Chapter 3.1.2, institutional distance was stated to be closely related to regional contextual developments and to country-specific regulations that affect collaboration performance. Furthermore, different perceptions of what are appropriate and fundamentally meaningful behaviour, and regional variations in levels of education, technological development, and economic development, produce institutional distance. In general, the artefacts represented in the publications included in this dissertation have only limited capabilities to bridge institutional distance. In the following chapter, the abilities of different artefacts to overcome differences related to institutional distance are discussed in more detail.

Artefact 1 and Artefact 2 are able to help to overcome differences in, for example, levels of technological development by supporting the creation of context ontologies that explicitly define different entities and the relationships between entities, and by educating users on how to semantically model and simulate different smart spaces. Respectively, the context visualizations provided by Artefact 3 can reduce institutional distance, which is influenced by differences in common understanding that affect collaboration performance. Furthermore, the visualizations of workflow execution provided by Artefact 4 can potentially increase common understanding of what is meaningful behaviour in different situations among stakeholders that perform monitoring. Finally, the smart space visualizations offered by Artefact 5 provides possibilities to overcome some aspects of institutional distance by enhancing the ability of smart space users to visually discover possible deviations in indoor conditions, and thus reduce the differences in levels of educations that may exist between, for example, smart space users and maintenance workers.

8.2.3 Analysis of organizational distance

Differences in organizational cultures cause organizational distance. Furthermore, employees of different organizations are often used to different information systems and communication channels, as well as corporation-specific methodologies and policies, which may impede interoperability. In general, the artefacts described in the publications can assist overcoming some aspects of organizational distance by providing common tools for smart space development and management that can be used across organizations. For example, Artefact 2 is able to bridge organizational distance by promoting a unified method of creating usage scenarios. Moreover, Artefact 4 establishes common ways to manage the execution of construction and maintenance tasks. Finally, Artefact 5 offers a uniform way to examine smart space information and send feedback to facility maintenance workers. Stakeholders from different organizations may adopt these unified determinations in order to participate in smart space maintenance work. Hence, Artefact 5 has some potential to bridge organizational distance, which is partly caused by differences in used methodologies, policies, and systems.

8.2.4 Analysis of spatial distance

Geographically distributed collaboration work creates spatial distance among stakeholders. Although geographical distances usually impede interaction between team members, dispersed teams are known to be more effective when tasks become more complex, because complex tasks often require multiple individuals, each with an area of expertise, to coordinate their actions, and often this expertise is located outside an organization, as discussed in Chapter 3.1.4. Respectively, the development and management of smart spaces usually requires multidisciplinary teams that work geographically apart, which creates a need for tools that help to overcome spatial distances, considering also the particular requirements of the application domain.

The artefacts described in the publications aim to overcome spatial distance by using different techniques. Artefact 1 facilitates traversing spatial distances indirectly, by providing means to create, for example, drafts of context ontologies and models. These ontologies and models can then be shared with other, geographically distributed team members, who are able to contribute with their own area of expertise. Artefact 2 enables the creation of context models that can be distributed among remote team members, who can start building scenarios based on those context models. Furthermore, Artefact 3 aims to overcome spatial distances by providing a method for remotely monitoring a smart home. However, improved communication functions would improve the artefacts' abilities to support collaboration between stakeholders working at a distance.

Artefact 4 reduces spatial distance with the ability to remotely monitor the progress of workflow execution. Moreover, the artefact provides features for collaboration stakeholders to interact using oral or written communication. Respectively, Artefact 5 provides a communication channel for smart space users to give feedback to smart space maintenance workers from a distance. Moreover, the artefact enables maintenance workers to remotely examine the current or historical indoor condition data of a smart space.

8.2.5 Analysis of temporal distance

As stated in Chapter 3.1.5, temporal distance is caused by collaboration across several time zones or across several working shifts, or through redesign and evolution by people not necessarily involved in the earlier stage of a design process. Temporal distance makes synchronous interaction less common and more difficult, generally exacerbates the challenges of coordination, and hinders real-time problem-solving. In the following chapters, the abilities of the artefacts described in the publications to overcome temporal distance are discussed in more detail.

Artefact 1 facilitates asynchronous collaboration by enabling stakeholders to contribute, for example, to the creation of architectural components when it's most convenient for them. However, improved version management features would enable people who join a design team in the middle of a development process to better collaborate with the original designers and be aware of the rationale behind their decisions. Furthermore, although Artefact 2 facilitates asynchronous scenario construction and simulation, the ability to bridge temporal distance could be improved if the artefact provided better mechanisms for storing and retrieving the created scenarios.

Besides real-time monitoring, Artefact 3 enables the aggregation and storage of collected context information. This enables users to examine historical monitoring data, which facilitates bridging temporal distance. Similarly, although the main objective of Artefact 4 is to enable real-time workflow monitoring, it also collects data about the execution of workflows, therefore providing possibilities for subsequent analysis. Finally, Artefact 5 enables the examination of facility information and giving feedback across time zones or working shifts. Additionally, the artefact supports examining historical measurement data about smart space indoor conditions, for example.

8.2.6 Analysis of relational distance

Relational distance on one hand refers to the way people build relationships with one another, and on the other hand relates to the difference between team members' organizational affiliations. Although close relationships are often built in informal settings where team members share practical experiences, current social networking applications enable individuals to maintain existing relational ties or build new ones, thus increasing the ability to make new friends at a distance. However, the bridging of relational distance requires that the applications have efficient interaction and communication mechanisms. In general, the artefacts do not provide direct communication means to build or maintain relationships between collaborative stakeholders. An exception is Artefact 4, which enables users to communicate with other collaboration stakeholders by voice, using a microphone, or by text, using instant messaging.

8.2.7 Analysis of cultural distance

Often, geographically distributed and multidisciplinary cooperation involves stakeholders from different cultures. The resulting cultural distance has a twofold effect on collaboration performance. On one hand, it hinders the team members' ability to reach mutual understanding, as people may communicate information or interpret a certain situation differently. On the other hand, cultural distance contributes largely to the richness of diversity, which fosters creativity.

Different technological aids can be used to facilitate overcoming the negative effects of cultural distance. For example, visual displays are shown to help in symbolic representation of objects to manipulate and support flexible interfaces that can be better adjusted to suit users with different cultural backgrounds (Gershon and Brown 1996). At the same time it is shown that visual displays can potentially increase cultural distance as they may be interpreted differently across cultures (Barber and Badre 1998). Furthermore, what is "user friendly" for one culture can be vastly different for another culture (Barber and Badre 1998). Hence, culture should be an important design consideration in applications aimed for multicultural end-users (Sun 2001).

The artefacts created during the course of this study provide different means that aim to bridge cultural distance. Artefact 1 reduces cultural distance by formalizing context models with ontologies that enhance knowledge sharing and shared understanding in virtual teams, as discussed earlier. Moreover, the provided visualizations improve understanding and enable users to generate new knowledge about the relationships between the data. Furthermore, the visualization-based scenario simulation supported by Artefact 2 enables users to freely adapt and manipulate semantic models of smart spaces and to examine the behaviour of smart spaces in different situations. These capabilities foster mutual understanding and facilitate common knowledge between stakeholders.

Artefact 3 and Artefact 4 try to overcome cultural distance by utilizing semantic modelling and visualization. In more detail, Artefact 3 provides informative visual representations showing the current state of smart spaces that facilitate the ability of collaboration stakeholders to form unified interpretations of different situations. Moreover, the graphical representations of workflows created by Artefact 4 facilitate the ability of collaboration stakeholders to form unified interpretations of different situations, and thus overcome cultural differences. Finally, Artefact 5 promotes a structured way to semantically describe versatile facility-related information. It also offers expressive visualizations that aim at reducing, for example, the viewer's cognitive load, and interpretation differences that are sometimes caused by cultural differences. However, although the above described visualizations are intended to improve mutual understanding, it must be remembered that differences in the interpretation of the visualizations provided by the artefacts may also increase the negative effects of cultural distance.

8.2.8 Analysis of emotional distance

The inability to observe another person’s feelings creates emotional distance and can disturb or impede the collaboration process. As discussed in Chapter 3.2.3, in dispersed teams where most of the collaboration work is carried out through electronic communication and collaboration tools, it is usually difficult to sense one another’s feelings and emotional states. The artefacts included in this dissertation provide only limited capabilities to reduce emotional distance. In more detail, only Artefact 3 provides some possibilities to overcome emotional distance by including symbols in visualizations that represent the emotional states of users of the smart spaces being monitored.

8.2.9 Analysis of lingual distance

As defined in Chapter 3.2.4, lingual distance determines the level of difficulty for a heterogeneous group of people to share meanings and understanding. Furthermore, while lingual distance often creates feelings of isolation, discouragement from collaborating, or difficulty in establishing relationships and mutual understanding, it may also foster more creative ideas due to the higher level of diversity. As with cultural distance, digital software tools and especially information visualization can be used to reduce the negative effects of lingual distance. In the following, the abilities of the different artefacts created during the course of this study to overcome lingual distance are discussed in more detail.

Artefact 1 attempts to bridge lingual distance by offering graphical means to create context models, thus enabling team members without a common language to collaborate and contribute. Moreover, Artefact 2 provides visualizations to be utilized in the creation and interpretation of different scenarios. Traditionally, scenarios used in information systems development are defined using textual descriptions that require language comprehension among collaboration members. Similarly to Artefact 1 and Artefact 2, the other artefacts utilize visualizations in order to bridge lingual distance, as described in the following chapter.

Artefact 3 provides graphical representations that enhance users' comprehension of, for example, sensor-based heterogeneous context data. Furthermore, Artefact 4 reduces lingual distance by enabling team members to graphically examine the current state of work processes and their decomposition and dependencies, and the allocation of resources is also introduced. Finally, in Artefact 5, the visualization-based data discovery bridges lingual distance to some extent. In addition, the ability to use special sliding clutches in estimating the current status (e.g., from too warm to cold) of different parameters enables smart space users with lingual distance to give feedback.

8.2.10 Analysis of cognitive distance

Cognitive distance refers to the differences in how people interpret, understand, and evaluate world differently. As discussed in Chapter 3.2.5, for organizations and teams to achieve a common purpose, people do not necessarily have to have similar knowledge, but they need to share certain basic perceptions and values to sufficiently align their competencies and motives. If cognitive distance between collaboration stakeholders becomes too large, the gap in mutual understanding impedes the process of learning by interaction. Multidisciplinary teams should contain stakeholders with sufficient cognitive distance to say something new, but not so distant as to preclude mutual understanding.

The artefacts presented in the publications aim to support effective collaboration work by increasing the ability of people with different backgrounds to participate in the development and management activities of smart spaces. Through different techniques and methods, the artefacts increase user awareness and reduce the gap in mutual understanding, which often hinders interaction and impedes the learning process. For example, the graphical context model creation and simulation features enabled by Artefact 1 and Artefact 2 aim to reduce the differences in how people interpret, understand, and evaluate smart space functions differently, which leads to improved mutual understanding and learning by interaction. Respectively, the visualization of logical rules addressed by Artefact 3 increases the awareness of when stakeholders are automatically informed of any malfunctions or emergency situations.

The visual representations of workflows provided by Artefact 4 support the perception of relationships and dependencies between different workflow entities and actors, which, in turn, facilitates uniform interpretation and understanding among collaboration members. Moreover, the communication features help stakeholders to bridge and connect their diverse knowledge. Moreover, Artefact 5 promotes common understanding among different stakeholders by enabling the visually examination of sensor measurement data, for example. The graphical representations help multidisciplinary collaboration members (e.g. smart space users, maintenance workers and building owners) to gain a more complete picture of the conditions of a smart space and share their perceptions.

8.2.11 Analysis of conceptual distance

In Chapter 3.3.1, conceptual distance is characterized as representing the closeness in meaning among concepts, taking as a reference a structured hierarchical network. Furthermore, in a practical sense, two conceptual dimensions can be identified in the communication between collaboration stakeholders: the expertise gap between experts and novices within a particular domain, and the conceptual gap between stakeholders from different practices or disciplines. Through construction of a collective conceptual model that is often based on ontologies, an improved shared vision among individuals representing diverse perspectives and interests can be achieved.

Artefact 1 is able to bridge conceptual distance by providing an environment conducive to collaboration. The artefact enables participant interactions that lead to a shared vision through construction of a collective conceptual model, which is based on ontologies. Additionally, by utilizing context model visualizations, the artefact reduces the conceptual gap between stakeholders from different practices or disciplines. Respectively, the scenarios created with Artefact 2 can be utilized for multiple purposes. Besides studying such technical aspects as service composition principles or pattern characteristics, scenarios can be used to demonstrate the capabilities of smart spaces for end-users. The scenarios are also intended to stimulate discussions in which end-users are able express their opinions on various design alternatives. Hence, the abilities of the artefact to support visual scenario creation and representation enhance the bridging of the two dimensions encompassed by conceptual distance: the expertise gap between experts and novices within a particular domain, and the conceptual gap between stakeholders from different practices or disciplines.

The visualization-based context monitoring enabled by Artefact 3, as well as the use of ontological context models, can help to overcome conceptual distance through improved mutual understanding. Moreover, by providing graphical views on semantic rules, sensor measurement data, and other context information, the expertise gap between experts and novices and the conceptual gap between stakeholders from different practices or disciplines can be bridged. Artefact 4 supports the semantic modelling of workflows, which can reduce conceptual distance, as it formally specifies relationships between concepts and elements. The conceptual models managed with the artefact facilitate collaboration participant interactions and leads to an improved shared vision. Moreover, the artefact is able to bridge the expertise gap between experts and novices and the conceptual gap between stakeholders from different practices or disciplines with illustrative visualizations. Besides promoting a shared vision among collaboration members by defining a conceptual model of existing real world environments, Artefact 5 reduces the conceptual gap between stakeholders from different practices or disciplines by understandably representing data that is normally only examined by smart space specialists.

8.2.12 Analysis of contextual distance

Contextual distance results from the differences in the contexts of two comparable situations, which often dictate how people perform in different tasks. In some cases, information technology can be used to bridge contextual distance by providing domain-specific assistance that is optimized to the user situation, offering the best possible content/service in the most suitable format with respect to the activity in which the user is currently engaged. The artefacts included in this dissertation provide only limited capabilities to overcome contextual distance. Artefacts 1, 2, 3, and 5 do not, for example, adapt the graphical user interface or content representations according to the user's context. Unlike the other artefacts, Artefact 4 provides different ways of communication for different contextual situations. For example, if loud background noise is detected, the users are able to switch from spoken to written communication. However, the artefact does not automatically adapt different functions according to the users' current context.

8.2.13 Analysis of referential distance

As defined in Chapter 3.3.3, referential distance corresponds to the distance between the point of origin and the correlating document, measured by the number of necessary references. In this way, it is possible to describe the potential relevance of a document compared to the origin of referencing. Referential distance is not applicable to any of the constructed artefacts. None of the artefacts consider the relevance of managed documents.

8.2.14 Analysis of semantic distance

Semantic distance resembles conceptual distance in many ways. Perhaps the greatest difference between semantic distance and conceptual distance is that the abstraction level of knowledge is higher on the conceptual level. As stated in Chapter 3.3.4, ontologies help to define a distance between terms or words by tracking nodes and edges in graph representations. The artefacts described in the publications included in this dissertation aim to reduce semantic distance by supporting the adoption and use of ontologies. In the following chapters, the abilities of the artefacts to bridge semantic distance are discussed in more detail.

The use of ontologies, supported by Artefact 1, can potentially overcome semantic distance, as it enhances the understanding of semantic relatedness of concepts. However, the ability to bridge semantic distance could be improved with graph-based visualization of ontologies, which would help users to discover semantic distance between terms and words. Furthermore, a structured way to define contextual scenarios in Artefact 2 would further facilitate the understanding of the semantic relatedness of concepts. This would require defining an ontology specifically designed for modelling scenarios and the concepts and elements they encompass.

In Artefacts 3 and 4, the semantic modelling and visualization of heterogeneous context data and workflows, including the resulting workflow ontologies, can assist overcoming some aspects of semantic distance, as it facilitates the interpretation of context information and clarifies the semantic relatedness between different concepts. Moreover, Artefact 5 defines its own ontologies for modelling building infrastructures, sensor data, and feedback provided by facility users. These ontologies clarify the semantic distance between different facility-related terms and words. For example, by examining the ontologies, users are able to determine how buildings, spaces, devices, sensors, or condition measurements are conceptually interlinked. However, the artefact itself does not enable the visualization of these ontologies.

8.2.15 Analysis of technological distance

According to Chapter 3.3.5, technological distance is on the one hand the result of the differences between the uses of various technologies, and is on the other hand related to the ability of an organization to take advantage of the public knowledge created by another organization. While collaborative technologies enable remote colleagues to connect and communicate, they do not always resolve the inability of individuals to learn from one another, due to the gap in technological knowledge. An important objective of the artefacts described in the publications is to simplify some of the activities relevant to the development and management of smart spaces and thereby bridge technological distance.

Artefact 1 reduces technological distance by serving as a common tool that enables different collaboration stakeholders to contribute to context-aware architecting. Moreover, the artefact reduces the gap in technological knowledge and expertise by facilitating the learning of semantic technologies that are essential in the development of smart spaces. Artefact 2 simplifies scenario creation and management through interactive visualization techniques. Similarly, Artefact 3 facilitates the understanding of semantic monitoring data and the logical rules that enable the inference of new facts from existing data sets, for example.

Artefact 4 is able to bridge technological distance by integrating such functions as workflow monitoring, anomaly detection and management, and user communication under a single graphical user interface. Moreover, the artefact increases users' technological knowledge by making complex workflow descriptions more understandable and thus facilitating the ability of individuals to learn from one another. Finally, Artefact 5 aims to support collaboration among multidisciplinary stakeholders by reducing the gap in technological knowledge. The artefact enables, for example, facility users to gain more knowledge about what kinds of measurement data are gathered in different parts of a facility. This potentially facilitates communication between facility users and facility maintenance workers. However, if the use of the artefact reduces the exchange of tacit knowledge that is difficult to transfer without face-to-face interaction, the artefact may also increase technological distance.

8.2.16 Analysis of ownership distance

As earlier concluded, wrongly addressed legal and ethical distance factors can turn any collaboration into a very low performance. In particular, an unbalanced IPR approach seems to have a significant influence on the success of collaboration work (Pallot et al. 2010). However, often different people have had diverse opinions on how, for example, research results should be protected: some promote greater commercialization through formal IPR mechanisms such as patents and copyrights, while others promote greater openness. The constructed artefacts can bridge the ownership distance by providing low-cost entry to the development and management of smart spaces and hence increase the abilities of small organizations to participate in collaborative work efforts. Of course, this presumes that the collaborating organizations are willing to use open source software. The artefacts are available under an open source licence and can be downloaded from the internet.

8.2.17 Analysis of financial and contractual distance

Financial distance is related to the unbalanced number of investments made in a relationship. Furthermore, contractual distance refers to the specification of collaboration stakeholders' rights and obligations within different circumstances that may occur during a collaboration project. Although financial issues, as well as legal aspects and especially an unbalanced IPR approach, have a significant influence on the success of collaboration work, they are considered to be beyond the scope of the artefacts represented in the publications included in this dissertation.

8.3 Research questions

The research questions that this study aims to answer were identified in Chapter 1.2. The purpose of this section is to analyse how and in which sections of the dissertation these questions were addressed. The research questions of this dissertation were:

1. Who are the stakeholders that contribute to the development and management of smart spaces?
    a. What are the roles that different stakeholders have?
2. What are the needs and requirements of different stakeholders and how can they be addressed?
    a. What kinds of support means do the stakeholders find most useful?
    b. How can collaboration between stakeholders be supported?
3. What are the requirements that different life-cycle stages impose on smart space development and management?
    a. How can development and management of smart spaces in different life-cycle stages be supported?

The themes related to the first research question, ‘Who are the stakeholders that contribute to the development and management of smart spaces?’ and its sub-question ‘What are the roles that different stakeholders have?’, were discussed in Chapter 2.2, in which 9 stakeholder roles were identified. The chapter also described the responsibilities, rights, and obligations that were determined for each of the identified roles. It was also stated that because the overall management of smart spaces is such a demanding process, a multitude of stakeholders with multidisciplinary skills and knowledge is required. The findings of the first research question are summarized in Table 7.

Table 7. Analysis of the first research question

Research question	**Treatment**	**Key findings**
Who are the stakeholders that contribute to the development and management of smart spaces? What are the roles that different stakeholders have?	Chapter 2.2	The development and management of smart spaces requires a multitude of stakeholders with multi-disciplinary skills and knowledge. The following stakeholder roles can be identified: space owner, general space developer, space administrator, space technician, device manufacturer, middleware provider, service provider, smart space user, and maintenance worker.

The aim of the second research question, ‘What are the needs and requirements of different stakeholders and how they can be addressed?’, was to clarify the requirements that different stakeholders have and to discuss how these needs can be fulfilled. The sub-questions investigated the kinds of support means that the stakeholders find most useful, and how the collaboration between stakeholders can be supported. The stakeholder requirements and the methods and techniques that facilitate meeting those requirements were covered, for example, in Chapters 2.2 and 8.1. Furthermore, in Chapter 7, the results of the performed evaluations were represented. The evaluations aimed to clarify how extensively the created artefacts are able to support the needs of different stakeholders, and which methods and techniques the stakeholders consider to be the most useful ones. The latter sub-question of the second research question was answered in Chapter 8.2, in which the abilities of the artefacts to support the collaboration between stakeholders were analysed using the collaboration distance framework. The findings of the second research question are summarized in Table 8.

Table 8. Analysis of the second research question

Research question	Treatment	Key findings
What are the needs and requirements of different stakeholders and how they can be addressed?	Chapter 2.2 Chapter 8.1.	The special needs and requirements of different stakeholders are dependent on their roles, as the stakeholder roles determine their responsibilities, rights, and obligations. For example, smart space administrators usually need to gain understanding about the operation of a space, and hence they benefit from monitoring services. Moreover, technicians often need assistance in performing smart space construction tasks, and hence they benefit if real-time guidance can be provided.
What kinds of support means do the stakeholders find most useful?	Chapter 7	The support means are dependent on the tasks and responsibilities of a stakeholder. However, it can be concluded that support means that enhance the understanding of semantically described data with interactive visualizations, and offer versatile communication mechanisms, were perceived as useful in general.
How can the collaboration between stakeholders be supported?	Chapter 8.2	The collaboration between stakeholders can be supported by bridging the distance factors that exist between collaborative individuals. Developing shared context and mutual understanding is particularly important in addressing this research question. The effective use of semantic data modelling techniques and graphical representations can overcome, at least partly, many of the identified distance factors.

The final research question, ‘What are the requirements that different life-cycle stages impose on smart space development and management?’ and its sub-question ‘How can the development and management of smart spaces in different life-cycle stages be supported?’, were discussed in Chapter 2.3, in which the different life-cycle phases were identified. Additionally, these topics were addressed in Chapter 8.1, in which it was analysed how extensively the artefacts represented in the different publications are able to provide support for different life-cycle phases. The consideration of the third research question is summarized in Table 9.

Table 9. Analysis of the third research question

Research question	**Treatment**	**Key findings**
What are the requirements that different life-cycle stages impose on smart space development and management?	Chapter 2.3	Based on the literature review, a smart space life-cycle model is specified in this dissertation. Moreover, the characteristics of each of the life-cycle phases are presented. The conducted analysis indicates that in the development phase, the focus is on, for example, discovering requirements, creating scenarios, defining architecture, and testing designs with simulations. In the construction phase, the challenge is in creating the necessary smart space infrastructure with a multidisciplinary team of professionals. Finally, the operational phase involves realizing the mechanisms for smart space monitoring, and addressing the challenges brought about by the changing nature of smart spaces.
How can the development and management of smart spaces in different life-cycle stages be supported?	Chapter 8.1	The relevant support means are dependent on the life-cycle in question. In general, at least the following supporting features can be identified: semantic modelling, context simulation, data visualization, heterogeneous data integration, and real-time monitoring. In addition, stakeholders will benefit if they are provided with mechanisms that enhance communication and facilitate inferring context information from unstructured sensor data.

8.4 Summary of the analysis

The analysis was divided into three sections. In the first section, it was described how the different smart space life-cycle phases and stakeholder groups are supported in each of the publications. In the second section, the artefacts represented in the different publications were examined against the collaboration distance framework. The third section discussed how the research questions defined in this study were addressed.

The purpose of the first section was to analyse how extensively different smart space life-cycle phases and, on the other hand, involved stakeholders were considered in different publications. As indicated in the section, all of the identified life-cycle phases were covered by at least one of the publications. In more detail, the development and operational phases were discussed in two of the publications, whereas the construction phase was covered by one publication. Additionally, the different stakeholder groups for which each of the publications provided support were specified. According to the analysis, all stakeholder groups except for the roles of device manufacturer and middleware provider were covered by the publications. The lack of support for these stakeholder groups was because of the technology-independent nature of the artefacts described in the publications. One of the main principles behind the created artefacts is that they are not tied to certain device manufacturers or middleware providers.

In the second section of the analysis, the artefacts represented in the different publications were examined against the collaboration distance framework. The overall purpose of this analysis was to obtain information about the capabilities of the different artefacts to support multidisciplinary collaboration work in smart space development, construction, and operation. In more detail, the analysis facilitated identifying, on one hand, the distance factors that can be bridged with the artefacts, and on the other hand, the dimensions that cannot be effectively overcome with the artefacts.

To sum up the results, the artefacts were discovered to bridge most effectively the distance factors belonging to the technical dimension. In particular, the conceptual, technological, and semantic distances were addressed relatively well with the constructed artefacts. This is probably because the artefacts were first and foremost designed to support the technical aspects of the smart space development and management, and considerable efforts were directed towards reducing the gaps in technological knowledge and conceptual understanding among stakeholders. Additionally, the artefacts were found to effectively bridge spatial and temporal distance factors, although it was concluded that improved communication features for developers to share knowledge could be provided. Finally, especially the utilization of diverse visualization techniques was considered to increase the artefacts' abilities to overcome lingual and cognitive distances.

The analysis also revealed distance factors that cannot be effectively overcome with the constructed artefacts. For example, the artefacts were not able to reduce institutional distance that is closely related to regional contextual developments and to country-specific regulations that affect collaboration performance. Moreover, an efficient bridging of relational and emotional distances would have required more advanced communication functions. Furthermore, the artefacts did not adapt graphical user interfaces or content representations according to the user's context, which would have enabled contextual distance to be overcome. Finally, referential, finance, and contractual distances were considered to be beyond the scope for the artefacts, as they do not consider the relevance of managed documents or collaboration stakeholders' rights and obligations, for example.

During the analysis it was discovered that the artefacts may also have the potential to increase some of the identified distance factors. For example, the differences on how the provided visualizations are interpreted across cultures may impede the reaching of mutual understanding among stakeholders. However, the artefacts' negative effects on collaboration distance factors were not actively sought in the research and hence further research on negative effects would bring additional understanding.

The third section of the analysis considered how the identified research questions were answered. The questions covered such topics as who are the smart space stakeholders, and what kinds of life-cycle phases can be identified, for example. To sum up some of the key findings, although each of the identified life-cycle phases is different in terms of the work performed, the stakeholders involved, and the know-how required, they all usually require multidisciplinary collaboration activities and geographically distributed cooperation. Additionally, by utilizing semantic technologies and illustrative visualizations, many of the identified distance factors can be at least partially bridged.

9. Conclusions

This dissertation discussed techniques and methods for supporting the development and management process of smart spaces. The research was conducted using a design science strategy, in which questions relevant to human problems are answered via the creation of innovative artefacts. Each of the developed artefacts focused on a certain smart space life-cycle phase and aimed to address the needs of particular stakeholder roles. Additionally, in order to realize the principles of the design science research process, the artefacts were evaluated. The performed evaluations provided valuable information about the deficiencies and strengths of the artefacts.

As stated earlier, smart space development and management is a demanding process that usually requires geographically distributed cooperation work and the involvement of multidisciplinary teams of professionals that bring knowledge from their specific fields of expertise. Hence, the collaboration distance framework that clusters various distance dimensions and related factors appearing in the course of distributed or distant collaboration was selected as the main analysis method to be used in this dissertation. The collaboration distance framework provides a holistic model that compiles and discusses various distance factors affecting the collaboration mechanics and performance.

The selected framework was discovered to be well-suited for this study, as it enabled the examination of the conducted research work from a wider perspective. For example, it enabled an understanding that providing holistic support for smart space development and management requires consideration of a number of distance factors that should be overcome. In addition, the collaboration distance framework facilitated the detailed analysis of the developed artefacts as it provided valuable information on the distance factors that can be effectively overcome with the existing artefacts. On the other hand, the framework revealed the collaboration dimensions that need more attention in further development work.

The second analysis method was examining the abilities of the artefacts to support different smart space life-cycle phases and stakeholder roles. The analysis showed that although all the identified life-cycle phases were covered in the study, the development and operation phases were discussed more extensively than the construction phase. The development and operation phases received more attention because of their importance in the overall life-cycle of smart spaces. For example, the design and maintenance activities are often emphasized in the life-cycle because of the evolving nature and complexity of smart spaces. Furthermore, the abilities of the artefacts to support different stakeholder roles were examined. The analysis revealed that in particular, the duties and responsibilities of such technical roles as general developer, administrator, and facility maintenance worker were considered by the artefacts. Additionally, the smart space end-users were supported by most of the created artefacts. As stated earlier, the device manufacturer and middleware provider roles were neglected because of the technology-independent nature of the artefacts described in the publications.

9.1 Future research directions

The future research topics include addressing the deficiencies found during this study. These improvements include designing and implementing mechanisms for visualizing ontologies on which the created context models are based. Moreover, more sophisticated techniques for creating, managing, and simulating scenarios must be provided. Finally, the functions offered by the graphical user interfaces will be revised and simplified.

As discussed earlier, approaches aiming to support multidisciplinary and geographically distributed collaboration work must enable and facilitate interaction among stakeholders. Hence, an important future research topic is to further study what kinds of interaction mechanisms the users appreciate and find useful. At present, the offered communication features are not sufficient. Additionally, as shown in the analysis, some of the identified distance factors were not sufficiently addressed. For example, the contextual distance that results from the differences in the contexts of two comparable situations was not efficiently bridged by the artefacts created over the course of this study. Hence, future research work will encompass developing mechanisms that provide domain-specific assistance that is optimized to the activity in which the user is currently engaged. Finally, modern day computer users often avoid tools that require tedious installation procedures. Thus, in the future, it should be studied how the created artefacts can be transformed into cloud-based web applications that require no installation on the personal computer.

Up to this point, the main focus of the study has been providing support for the development and management of such smart spaces as homes, schools, or production lines. However, in the car industry, for example, there is a motivation to design more intelligent transportation systems. In fact, many modern-day vehicles already meet the characteristics of smart spaces. Hence, an important future research topic is to design and implement techniques that improve the ability to support a variety of smart space types.

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PUBLICATION I

An interactive ontology visualization approach for the networked home environment

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An Interactive Ontology Visualization Approach for the Networked Home Environment

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Abstract—Ontologies are broadly used in the context of networked home environments. With ontologies it is possible to define and store context information, as well as to model different kinds of physical environments. Ontologies are central to networked home environments as they carry the meaning. However, ontologies and the OWL language is complex. Several ontology visualization approaches have been developed to enhance the understanding of ontologies. The domain of networked home environments sets some special requirements for the ontology visualization approach. The visualization tool presented here, visualizes ontologies in a domain-specific way. It represents effectively the physical structures and spatial relationships of networked home environments. In addition, it provides extensive interaction possibilities for editing and manipulating the visualization. The tool shortens the gap from beginner to intermediate OWL ontology reader by visualizing instances in their actual locations and making OWL ontologies more interesting and concrete, and above all easier to comprehend.

***Keywords*—**Ontologies, visualization, interaction.

I. Introduction

ARTIFICIAL intelligence refers to programs and procedures that are able to automatically solve problems heretofore solved by humans [1]. To enable this automated problem solving, recent work in artificial intelligence has been concentrated on exploring ways to specify content-specific agreements for the sharing and reuse of knowledge among software entities [25]. Ontologies have become a popular research topic among several artificial intelligence research communities because of their ability to provide a shared and common semantic understanding [2].

A commonly agreed definition of ontology, made by Gruber [3] is the following: “An ontology is an explicit and formal specification of a conceptualisation of a domain of interest”. Furthermore ontology is defined as a controlled vocabulary that describes objects and the relations between them in a formal way; ontology resembles faceted taxonomy but uses richer semantic relationships among terms and attributes, as well as strict rules about how to specify terms and relationships [4], [5]. Ontologies represent a shared meaning of a domain and they can be used to describe almost any kind of domain explicitly.

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Ontologies are broadly used in the context of the networked home environments. As Gu et al. [25] have pointed out, with ontologies it is possible to define and store context information, as well as to model different kinds of physical environments. Ontologies are central to networked home environments, as they carry the meaning. With ontologies some of the most important problems in the development of the pervasive computing environments can be overcome [26]. OWL semantic mark up language was created for publishing and sharing ontologies and it provides mechanisms for creating all the components of an ontology: concepts, instances, relations and axioms [8].

However, working with ontologies and the OWL language is often complex. Looking at an OWL ontology for the first time can be overwhelming and the gap from beginner to intermediate OWL ontology reader is cumbersome. Information visualization by definition is the process of turning abstract data into a visual shape easily understood by the user, making it possible for him/her to generate new knowledge about the relations between the data [9]. Visualization can also be the key to better understanding of the data contained by ontologies. A visual version of an ontology allows users to visually follow a concept to its nearest neighbours or analyze the overall space for interesting related or unrelated concepts. [10].

Several ontology visualization approaches have been delivered by research community in some past. Common feature of these approaches is that they are graph based and domain independent. However, the graph based visualization is not capable of effectively visualizing every kind of data. As Wehrend & Lewis [11] have mentioned, the chosen visualization technique should always be relevant to the given problem and support the user’s goal in viewing the representation. Another shortcoming of these approaches is their limited interaction features. In order to gain full understanding of the visualized data, users should be able to interact with the visualization [6].

The main research problem of this study is to find out how can ontologies be visualized, particularly in the domain of networked home environments, and how can interactive visualization elements be included in the visualization. To answer this problem, three research questions must be answered:

1. What special requirements does the networked home domain set for the visualization approach?
2. How should context information be presented and managed in the visualization?
3. How should the interaction be implemented and managed?

In this study a visualization tool called VantagePoint is constructed. VantagePoint is able to interactively visualize ontologies particularly in the domain of networked home environments. Special attention is given to the interaction between the user and the visualization. The constructed approach should act as an example of how the actual research problem can be solved. The approach visualizes OWL ontologies graphically, making them more interesting and concrete, and above all easier to comprehend.

This paper is structured as follows. Chapter 2 presents some of the tools currently available for ontology visualization identifying their shortcomings and benefits. The developed ontology visualization tool is described in more detail in Chapter 3 and finally, the conclusions are presented in Chapter 4.

II. The State of Art in Ontology Visualization Tools

Currently there exist several approaches to visualizing ontologies. Many of these approaches are embedded in tools that support the development process of ontologies. The intended users of these tools are ontology engineers that need to get an insight into the complexity of the ontology. Therefore, these tools employ schema visualization techniques that primarily focus on the structure of the ontology, i.e. its concepts and their relationships [13]. The examples of such ontology visualization approaches are Ontoviz [14] and Jambalaya [15], which are visualization components of ontology editor Protégé [12], and Cluster Map [13], which is a component of navigation engine Spectacle.

Common to these approaches is that they are domain independent and graph based. Ontologies are visualized only by representing their entities with nodes and the relationships between entities with arcs. Furthermore, these approaches contain quite limited graphical editing operations. Only TGVizTab offers real possibilities to graphically edit the visualization. In the other two approaches, the interaction operations are restricted to navigation and the selection of features to be visualized. Furthermore, considering how important a role queries play in data analysis, the search features in these approaches are surprisingly modest.

The tool presented by this research addresses the above enumerated shortcomings by visualizing the semantic information models in a realistic and concrete manner. It allows users to dynamically manipulate the underlying models through various graphical editing operations. By visualizing environments realistically, users are able to see the different operations as in real life.

III. The Most Important Requirements for the Approach

The domain of networked home environments sets some special requirements for the visualization approach. In this chapter those requirements are described.

As discussed above, the ontologies considered in this study model different kinds of physical environments. Thus, it was thought important to present contextual information and spatial relationships effectively in the visualization. Another requirement was that the graphical appearance of the visualization should be realistic. Realism breeds the expectation of accuracy, reliability and authority in the representation, especially when considering computer visualizations which aspire to simulate real environments [27].

The next requirement highlighted the importance of interactive elements. The interaction between the user and the visualization helps us to understand the visualization better [6] and thus VantagePoint was designed to offer such editing operations as adding, moving and deleting of instances. These operations were defined not just to enable the editing of the visualization itself, but also to give direct access to the underlying ontological data behind the visualization.

The ability to view the data from different perspectives and from different angles enhances understanding of the data [16]. To realize this, a requirement for multiple angles and perspectives was added to VantagePoint. By defining this requirement, it was assured that users would get a good overall picture of the data, as well as being able to perform accurate editing operations.

The last requirement was to ensure that VantagePoint offers extensive possibilities to construct and execute queries. As was concluded in Chapter 2, in the existing ontology visualization approaches the search features were surprisingly modest. VantagePoint addresses this shortcoming by providing two different query methods: a graphical query and a free query. With the graphical query option inexperienced users are also able to execute queries without having any particular knowledge of the ontology query languages RDQL [28] or SPARQL [29]. With the textual query option, advanced users are able to define their own query statements without any constraints.

IV. The Main Components of VantagePoint

VantagePoint core contains the most important functions of the software: model visualization, model manipulation and model simulation. These functions are implemented in Java and controlled through Swing GUI. The VantagePoint core is presented in Fig. 1.

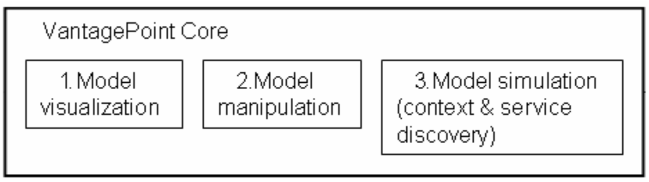

Fig. 1 The main components of the VantagePoint

1. As discussed before, VantagePoint forms semantic models of networked home environments. The *Model visualization* component is responsible for the visualization of these models. It reads OWL files and searches for individuals that belong to predefined VisualComponent class. Only individuals that belong to the VisualComponent class are visualized, all other data that is irrelevant or impossible to visualize is ignored. The VisualComponent class is divided into two separate subclasses - *Item* and *Area*. All things visualized fall into these two classes. If the ontology does not contain the class VisualComponent, it cannot be visualized with VantagePoint. In such cases a blank visualization is created and users can examine the ontological model through the query features provided by VantagePoint.

2. The *Model manipulation* component enables changes to be made to the visual representation of the model. The manipulation consists of editing operations such as removing, adding, moving and rotating of instances. Whenever editing operations are made in the visualization the ontological data changes accordingly.

3. The *Model simulation* component defines ways of implementing context and other discovery operations. These operations are carried out by utilizing the SPARQL and RDQL query interfaces provided by VantagePoint.

V. Architectural Framework

The Model-View-Controller (MVC) framework was selected as a starting point for the architectural design of VantagePoint. The MVC framework is a widely used architectural approach for interactive applications. It divides functionality between objects involved in maintaining and presenting data to minimize the degree of coupling between the objects [17]. In the Model-View-Controller architecture, objects of different classes take over the operations related to the application domain (the model), the display of the application's state (the view), and the user interaction with the model and the view (the controller) [18]. Modularity of components has enormous benefits, especially when building interactive applications. Isolating functional units from each other as much as possible makes it easier to understand and modify each particular unit, without having to know everything about the other units. This three-way division of an application entails separating the parts that represent the model of the underlying application domain from the way the model is presented to the user and from the way the user interacts with it [17].

The architectural design of the VantagePoint is a slightly modified version of the Model-View-Controller framework. Contrary to the Model-View-Controller paradigm, the model class do not notify the views when it changes. This is mainly because the model class in VantagePoint architecture is adopted from the class library provided by Jena [30] and therefore it was considered better not to implement any new functionality in the OntModel class, but to leave it as it was. Instead, a new class called VPEditor was created to implement some of the functionalities that would normally belong to the model class in the MVC architecture. Furthermore, it was decided to implement the user interface elements of the application in the VPEditor class. In this way the WorldManager class, which acts as a controller class in VantagePoint architecture, could be maintained as a simple interface to the model. This was considered to increase the versatility and the reusability of the approach. To illustrate the functionality of the architectural framework of the approach, a detailed description of VantagePoint's interaction cycle is presented in Fig. 2.

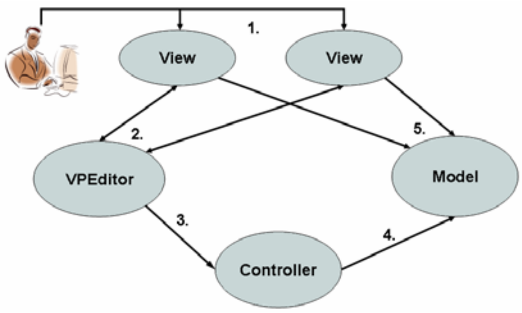

Fig. 2 A standard interaction cycle of VantagePoint

1. The basic interaction cycle starts when the user performs an editing operation in some of the views. For example, the user may change the location of an instance by dragging it to another position.

2. The VPEditor class 'listens' to the views and tracks the changes occurring in them.

3. VPEditor forwards the necessary information about the editing operation to the controller class.

4. The controller class (WorldManager) acts as an interface to the model (OntModel) and changes the model according to the editing operation.

5. Finally, VPEditor calls the views' update methods to set the views in sync with the current state of the model.

As can be seen from Fig. 2, different components in VantagePoint architecture implement their own strictly defined responsibilities. Separating responsibilities among model, view, and controller objects reduces code duplication and facilitates handling of the data, whether adding new data sources or changing data presentation, as business logic is kept separate from data [18].

VI. The VantagePoint

The software tool presented in this study allows to interactively visualize ontological models particularly in the domain of networked home environments. The approach is written in Java and it uses Jena interface to manage OWL ontologies, and Java 2D graphics to visualize them. Rather than visualizing the abstract structural relationships of ontology classes and instances, VantagePoint presents contextual information and spatial relationships effectively by visualizing instances in their actual locations. VantagePoint also offers the possibility to view the visualization from multiple angles and with different perspectives and it exploits both two- and three-dimensional views.

The edit view is a 2D ‘ground plan’ view of the ontology that has been visualized, whereas the isometric view visualizes ontologies more impressively from a three-dimensional perspective. The purpose of the two-dimensional edit view is to enable more accurate editing operations. In general, 2D views are considered better for navigating and measuring distances precisely, establishing precise relationships and performing spatial positioning [19], [20]. As can be seen from Fig. 3, the appearance of the edit view is somewhat rough. Items are represented with symbols, which include a textual description of the item, and an arrow indicating the current direction of the item. The edit view is presented from a bird’s eye perspective, which does not exploit the three-dimensional representation. Instead, it enables the possibility to accurately create areas with exact measurements and locate items in their correct positions.

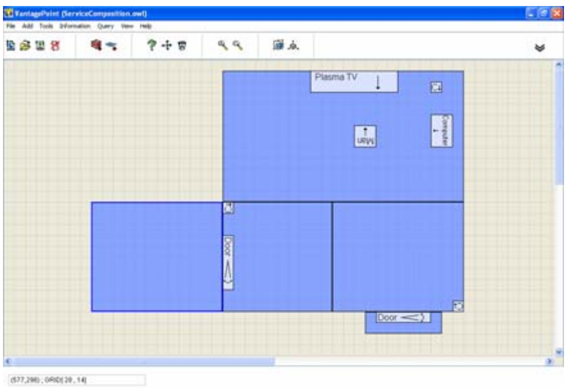

Fig. 3 A VantagePoint screenshot where the edit view is visible

In the isometric view the environment is presented from an isometric projection which offers a better general view of the house. However, the isometric view does not offer as accurate editing and adding operations as the two-dimensional edit view. Three-dimensional displays are said to be good for gaining an overview of a 3D space, understanding 3D shape, and navigating approximately [21]. The isometric view is presented in Fig. 4.

The isometric projection was selected as a representation method, because it allows users to have a general view of the visualized world at a glance. It is also stated that by using the isometric projection, spatial relationships between objects can be seen within wide environments [22]. Furthermore, the isometric projection has proven its effectiveness in visualizing three dimensional spaces in such popular computer games as ‘The Sims’ [23] and ‘SimCity’ [24].

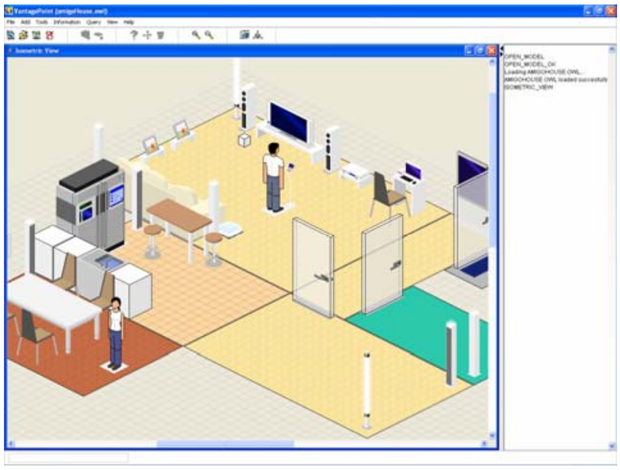

Fig. 4 A VantagePoint screenshot where the isometric view is visible

The exploitation of both visualization types, 2D and 3D, was thought to be a necessity, since VantagePoint was required not only to visualize ontologies, but also to offer means to accurately edit them.

VII. The Interactive Features

As discussed, one of the most important requirements of VantagePoint was to offer extensive interaction possibilities to the user. In this chapter the interaction operations provided by VantagePoint are described in more detail.

To begin with, VantagePoint offers operations for adding and removing of instances. In VantagePoint, instances are either areas or items. Areas are used to represent different kinds of spaces, like rooms and hallways in the house model, whereas items represent either devices or persons and they are represented with realistic 3D icons or 2D symbols that are supposed to make items recognizable. Both areas and items can be added and removed through simple graphical operations.

The items are added by selecting an item from the text list that enumerates all the items offered by VantagePoint. After the item has been selected, the location for the item can be determined by dragging it to a desired position.

The adding of areas is performed by assigning the corner points of the area. Once the desired points have been selected (three at least), the area must be named. It is also possible to determine a floor material for the area. Different floor materials are represented with different textures in the isometric view (see Fig. 4).

Delete operations are performed simply by selecting the desired instance and pressing the ‘garbage can’ button in the control panel. As the selected instance disappears from the screen, it is also removed from the ontological model. If an area is deleted, all areas and instances that were contained by this area are also deleted.

In addition, to the operations described above, VantagePoint offers interaction operations such as moving of instances, printing of models and getting additional information about instances.

In VantagePoint all visualized elements are movable and the moving operation is executed simply by dragging an instance to a new location. The printing operation enables the visualized model to be printed in a textual form. In this way it is possible to examine the structure of the OWL file and see how the changes made in the visualization have affected the model. The final interaction operation described here is called “getting additional information about instances”. This operation enables certain additional information about selected instances to be quickly obtained.

As it was earlier discussed, queries are an effective way of retrieving data from ontologies and in the existing visualization approaches the query construction features are quite restricted. VantagePoint stands out from other ontology visualization approaches by providing extensive support for query construction. It supports two ontology query languages SPARQL and RDQL. In addition, VantagePoint offers two distinguished query methods: a graphical query and a free query.

Graphical querying in VantagePoint means that users can define queries that will be executed when an instance is being clicked on in the visualization. By means of graphical querying it possible to retrieve information about, for example, what services are offered in a certain area. VantagePoint provides also a possibility to save query sets in text file to be reused later and thus the same queries can be executed through graphical user interface with minimal knowledge about the query languages needed.

The queries that will be executed when an instance is being clicked can be defined in the query settings dialog box, which is presented in Fig. 5.

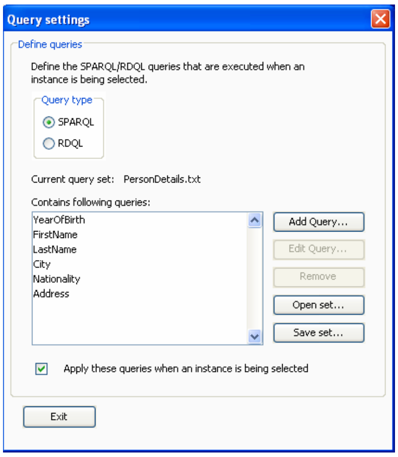

Fig. 5 A dialog to define queries executed in graphical querying

In the free query, the queries to be executed are not restricted in any way. With the free query it is possible to retrieve any kind of information from the model, even data that could not have been visualized.

As presented in Fig. 6, the free query is constructed by writing the query statement in to the upper text area and pressing the execute button. Results will appear to the lower text area.

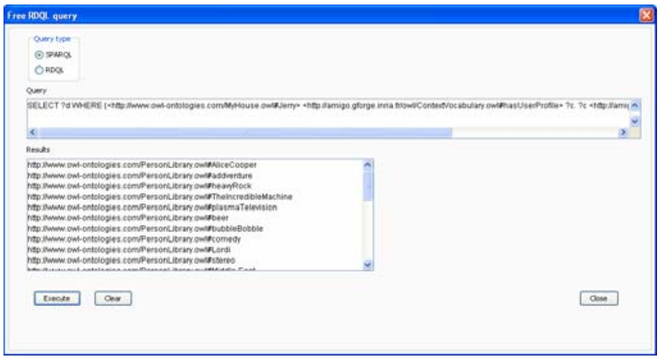

Fig. 6 The dialog for defining free queries

VIII. Conclusion

This paper presents a prototype software tool called VantagePoint. VantagePoint is able to interactively visualize ontologies, particularly in the domain of networked home environments. VantagePoint fills a certain niche that is not supported by the other ontology visualization tools by visualising ontologies in a domain specific way. VantagePoint exploits such representation techniques that are particularly effective at showing the physical elements of networked home environments, and spatial relationships between entities. Currently, there are no similar approaches available.

VantagePoint provides two distinct views to examine the visualized models. The two-dimensional edit view is a “ground plan” view of the environment being visualized. This view enables effective and accurate discovery of the spatial relationships between different elements, perception of the exact positions of various instances, and accurate editing operations. The isometric view represents environments impressively from an isometric perspective. This 3D view enables to obtain a better overall picture of an environment.

Furthermore, VantagePoint provides extensive interaction possibilities. With various editing operations users are able to edit both the visualization and the underlying ontological model. Through these operations, users are able, for example, to add new instances and thus graphically create their own semantic models from scratch. In addition, VantagePoint provides extensive query construction possibilities to extract any kind of information from the visualized model.

VantagePoint helps people who are not familiar with ontologies and the OWL language. It provides an easy access to the complex world of ontologies and OWL language. VantagePoint shortens the gap from beginner to intermediate OWL ontology reader by visualizing ontologies realistically and making OWL ontologies more interesting and concrete, and above all easier to comprehend.

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PUBLICATION II

Towards a better understanding of semantic ontology-based home service modelling

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Towards a better understanding of semantic ontology-based home service modelling

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Abstract

With rapid advances in the enabling technologies for pervasive computing and with the requirements for communication systems autonomy, ontology-based semantic approaches as applied to contextual application scenarios have recently received a great deal of attention from the research community. However, service modelling using semantic knowledge sources and the available service semantic description languages can be a time and effort consuming process, which thus leads to the poor acceptance of semantic technologies. The semantic support environment presented in this research addresses this shortcoming providing a more illustrative and understandable way to view ontology instances associated with complex contextual information. It enables semantic modelling and the interactive simulation of physical real-world contextual environments of interest (i.e. devices, services, functional capabilities of service, contexts). It provides support for the design of applications or middleware level services.

1. Introduction

Pervasive computing is the trend towards increasingly ubiquitous, connected computing devices in the environment; a trend being brought about by the convergence of advanced electronic, wireless technologies and the Internet. Pervasive computing devices can be mobile or embedded in almost any type of physical environment (e.g. home, office, cars) or object imaginable, all communicating through increasingly interconnected networks.

It is expected that in the future, *smart* devices around us will maintain current information about their locations, the contexts in which they are being used, and relevant data about the users. Computing will have become so naturalised within the environment that people will not even realise that they are using computers.

To realise this vision, researchers are looking for new, innovative concepts and approaches. Among the emerging technologies expected to prevail in the pervasive computing environment of the future are semantic technologies. The reasoning tools, semantic languages such as RDF, OWL, OWL-S, and ontologies promise far more effective machine-to-machine communication. The use of ontologies makes it possible for computational entities and services to have a common set of concepts and vocabularies for representing knowledge about a domain of interest, while being able to interact with each other. By using ontologies, the relationships between entities can be more clearly expressed and these allow for better reasoning on their properties.

While several research projects have addressed the ontology needs and aspects of semantic service representation for pervasive ubiquitous environments, some open issues and challenges can be still identified in this domain.

Even a simple ontology can be very complex at first and far from being accessible for many domain experts such as software developers. As a consequence, system design and application and service modelling using semantic knowledge sources and the available service semantic description languages can be a time and effort consuming process. Therefore tools are required for the adoption of semantic technologies, in particular Semantic Web Services. Moreover, physical Living Labs with devices and services employing semantic technologies are not always available for service developers to validate their proof-of concepts and developments. So there is a demand for virtual development environments supporting semantic service modelling and verification.

Semantic Web Services are the subject of intense research and have proved themselves as being beneficial to address the problems of discovering and composing web services in e-commerce. However, there has been little attention paid to the application of semantic frameworks for non-Internet services that are different in the sense that they represent the services hosted by physical devices. Therefore the managing of such services brings an additional requirement to

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semantic modelling, with a clear link to the resources that characterise the particular device and network.

The virtual development environment presented by this research addresses the shortcomings identified above. The environment named 'VantagePoint' is primarily targeted for the developers of intelligent pervasive applications that use semantic information and also for researchers who are domain experts but not yet knowledgeable of working with ontology languages and tools. The environment makes it possible to view ontology instances associated with a complex contextual information in a more illustrative and understandable way. It also makes it possible to semantically model and interactively simulate either physical real-world (i.e. devices, services, functional capabilities of service, contexts) or conceptual (business boundaries, networking or security domains) contextual environments of interest. It provides support for designing applications (e.g. to verify a service composition logic) or middleware level services (e.g. semantic service discovery) conceptually against one or more contextual scenarios.

The research presented in this paper is based on the work carried out in the Amigo project [13]. In brief, the main objective of the Amigo project [14] is to develop an Ambient Intelligent networked system that effectively integrates heterogeneous devices and services residing in the home domain. The designed Amigo architecture adopts a service oriented architectural style. The semantic-based application and the middleware layer interoperability mechanisms are the key elements of the Amigo architecture. The ontology-based service discovery and dynamic service composition are additional challenges addressed by the project. The utilisation of ontologies enables the effective description of the heterogeneous services and resources residing in the home. A rich representation of service capabilities with non-functional parameters such as QoS and context enables automatic service discovery and composition.

The research paper is organised as follows. Section 2 provides an overview of the semantic frameworks currently available for semantic application design with the positioning of our research there. The semantic tool is overviewed in Section 3. Examples of simulated scenarios and the usage of VantagePoint are presented in Section 4. We conclude in Section 5, discussing also the future perspectives of our work.

2. The state of the art in semantic tools

Numerous freeware and commercial tools to support the development and use of ontologies are currently available. Examples of ontology editors are: SWOOP [1] is a hypermedia-based featherweight OWL ontology editor; Protégé [2] is a free, open source ontology editor and knowledge-base framework; TopBraid Composer™ [3] is an enterprise-class platform. The advancement in these tools has greatly improved the ability to test and build ontologies from scratch or to reuse existing ontologies.

Application Programming Interfaces (APIs) for ontology languages provide programming language dependent means to load ontologies, manipulate the ontology classes and relations, perform reasoning, and provide persistent storage for the model. Jena [4] and OWL-S API [5] are the most popular Java frameworks for building Semantic Web applications. These tools provide the application developer with programming language level support for working with ontologies.

There are several tools providing reasoning capabilities for ontology applications offering either a language dependent API or the DIG interface. Examples of such are FaCT++ [6], Pellet [7], RacerPro [8]. These tools both help in ontology testing and in developing SW application level intelligence that use developed ontologies.

Domain ontology specific editors such as OWL-S Editor for editing and testing OWL-S -based semantic service descriptions [9] help to create error free semantic descriptions based on a specific ontology. WSMO design studio [10] is a semantic web service modelling environment. The tool provides support for editing some specific WSMO ontology elements such as goals, services and mediators, choreography design and adding semantic annotations to WSDL documents.

From a service modelling perspective what is missing from those tools are features that would make the contextual semantic information related to service descriptions easier to understand and foolproof in use by an application developer. This is especially important for people with a general SW engineering background rather than ontology experts. The ontology application development is mainly supported by programming language level APIs that are difficult to use without a solid background knowledge of ontology languages. Moreover, the visualisation support provided by generic ontology editors is limited to showing mainly the abstract structural relations of the ontology classes and their instances. These tools are not well suited for understanding the semantic relations in a complex physical world dynamic application scenario or for supporting the creation of a model of such a scenario model for application validation or testing purposes. This leaves the step of adopting semantic approaches in service oriented application development too high for most programmers.

The semantic support environment presented in this research addresses the above enumerated shortcomings by visualising the semantic information models related to contextual services in dynamic networked home related application scenarios, and providing a visual editing and interaction UI for working with such models. It also provides a means for creating domain specific libraries of semantic information (e.g. device types and services hosted by devices) and ready-to-use queries to be reused with the model, thus helping a developer become familiar with semantic information, and start working.

3. VantagePoint overview

VantagePoint is an editor and viewer for contextual information described with the OLW ontology language. Rather than providing a traditional class and relations oriented view for user (i.e. researcher, service developer), it displays a 3D view of the application scene with rooms, objects, and persons which form classes of the ontology. By clicking on these classes, the developer can view and define relations in the ontology. By moving objects/persons, the constructed application can be simulated. The visualisation could show, for example, a real-world, Lab or imaginary home environment (see Fig. 1). A developer can use the visualisations to create one or more contextual scenarios related to an intelligent application in order to gain a better understanding of the semantic models associated with the services that the application uses.

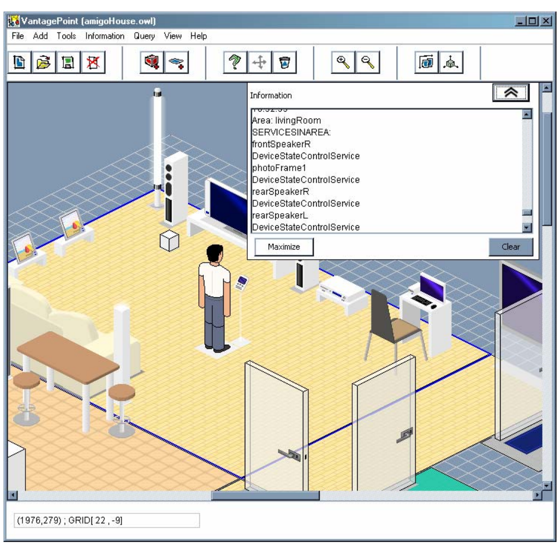

Fig. 1. The isometric view of Amigo House

VantagePoint provides two ways to visually show the spatial relations in the model: the bird's eye view and the isometric view. The bird's eye view is a ground plan view of the physical or abstract environment that is visualised. It makes it possible to manipulate the model more accurately by making changes to the visual representation of the model. All of the editing, removing and adding operations always change both the visualisation and the dynamic semantic model (i.e. ontologies). The isometric view provides a more informative 3D version of the information and is more intuitive and interesting for a human.

VantagePoint enables the dynamic management of semantic contextual models. When a visualised model is being manipulated by a developer in the graphical view (i.e. devices and areas are added or removed), the changes are simultaneously added to the semantic model (i.e. OWL ontology files). The ontology classes can have any amount associated semantic information (e.g. semantic descriptions of services provided by a device) and may have relations with external semantic descriptions. The desired semantic descriptions have to be imported into the VantagePoint model to be further queried. Various tools such as Protégé, OWL-S or WSMO editors discussed in Section 2 can be used to create and edit such information.

VantagePoint can have several visualisation libraries containing domain specific icons. These libraries are stored as simple text files, which contain the URLs of the icon files providing an isometric visualisation from different perspectives (PNG images) and a URL of a semantic description of class in one of VantagePoint's semantic libraries. A browser tool is provided to examine the visualisation libraries. The current libraries are related to intelligent home applications. In the future, there can be elements describing other intelligent environments such as car, hospital, or mobile outdoor domain.

VantagePoint uses the Jena interface to manage and query OWL ontologies. The tool offers a convenient user interface to specify a query based on SPARQL [11]. More advanced users can specify his/her own sophisticated queries. For less semantic-familiar users, the tool provides some predefined sets of query templates. Therefore such information as the services presented in particular areas, services deployed by particular devices, the status of devices and information related to the persons living/located in the house can be obtained easily and provided to applications. For example, the developer can write and test a free form query statement to find out the services available (deployed by the devices in area) in a selected area:

%ServicesInArea%
SELECT ?x ?y
WHERE {<#INSTANCE#> <#contains> ?x. ?x <#deploysService> ?y}
%

The result of the query is visualised in Fig. 1.

4. Simulation scenarios

As was previously explained, the semantic descriptions of services hosted by devices in the visualised scenario can easily be imported (i.e. published) to VantagePoint using standard ontology import mechanisms. The imported services are maintained further by the semantic service repository developed within the environment. The Java call-back mechanism is integrated into the environment to simulate context events (i.e. context management service (CMS) simulation). For example, by moving items (device or a person) around in the VantagePoint model service, the developer may create a context event that can be sent to the application, subscribed as a listener.

The SPARQL queries, service repository and context event mechanism provide a base for the simulation of service discovery and service composition functionality in VantagePoint. The simulations are further explained in the sequence diagram in Fig.3, where a typical scenario of the follow-me application is presented. In this scenario we are interested in designing an Ambience sharing application, which is a context-adaptive extension of traditional person-to-person visual communication services such as videoconference. It is composed of several A/V capture and A/V rendering services. Depending on the situation, the service composition system dynamically selects relevant capture and rendering services and establishes connection (i.e. stream redirection) between them through the A/V relay service. The scenario is visualised in Fig. 2. There are two houses defined for the scenario with a person in each (e.g. Roberto and Maria). The house of Roberto is modelled in more detail so that we can test the composition logic with a different set of devices providing the required A/V services for the application. The rooms in Maria's house have not been defined in more detail. The service composition problem for the example scenario is to find the most suitable Media Renders and Media Captures devices/services in Maria's and Roberto's homes and also to make service composition application adaptable to the current context (e.g. persons move, new device/services are registered).

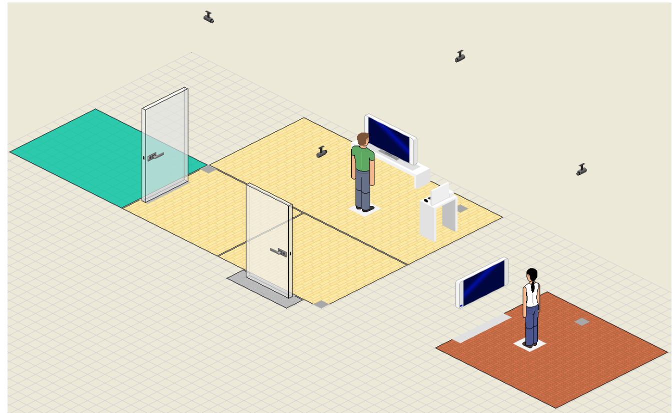

Fig. 2. Visualised Ambience sharing example scenario

The sequence of simulation goes as follows:

1. Application developer loads, i.e. is created by drawing a model of a house which is the scenario for this simulation (see Fig.2). The house model contains the items which provide services for this case (i.e. devices such as TV, PC, laptop that host media renders and media servers) and areas (i.e. rooms). The ontologies relevant to the described scenario are imported.
2. Ambience sharing service composition application subscribes to a context event. It wants to be notified if this particular context event occurs. In this case, the interesting event is person Roberto moving from one area to another area and the goal is to perform "follow me"– types of tasks. Another example of an event context to subscribe to can be new device/service being registered to the environment (e.g. better QoS) or ones leaving.
3. Application developer moves an item representing Roberto from one area to another area. An "item moved" event is generated by VantagePoint. Then Context management service (CMSSimulation), registered to listen VantagePoint events, queries if the item is a person moving from one area to another. If so, it notifies the service composition application of this event and new location.
4. Service composition application reacts to context changes and performs a new service request (i.e. service discovery) for the area where the person has moved into.
5. A new composition strategy is invoked by the service composition application (omitted in the figure).

In our case the service composition is described by defining one or more *composition rule* classes that describe the composition logic and by selecting a suitable *composition strategy* to describe how the selected services are composed into a task that can be executed. The composition strategy can be a simple Java code fragment that calls the selected web services. The trace of composition logic in the selected scenario can be examined in VantagePoint to verify that it works as expected against the set of services such as MediaRendering (any screen), MediaCapture (camera, microphone) and MediaControlPoint, which are all available in the current room.

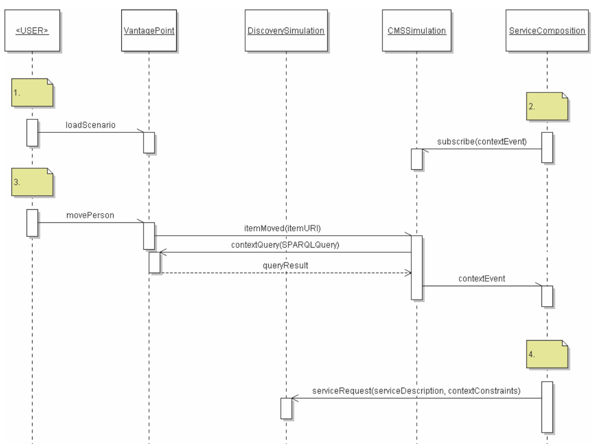

Fig.3. Sequence diagram: the dynamic service discovery and composition

The simulation is very useful for application developer who, for example, designs some composite service, or simple service being integrated into a composite one. Such a service can be semantically described and imported into the framework (i.e. publish to repository). Thus the relevant semantic interfaces or overall logic of the composite application workflow can be verified. Dynamic changes in context can be seen in a more illustrative manner with VantagePoint than observing changes in raw OWL files. Application developers can see the results of semantic manipulations in real life and notice practical errors better without expensive laboratory tests. A developer can create visualisations of application related scenarios and, by editing the model, can simulate the contextual changes associated with the scenario. The described tool prototype is still in the development and improvement stage. Several real and imaginary physical home environments have been modelled using it. It has also been offered to application designers for testing within Amigo. The obtained feedback is pretty positive. Preliminary validation tests on efficiency and usability have been also carried out. For example, the time to load the semantic model of an environment varies only a little depending on the imported OWL ontology (3.3 s for 999 versus 6.4s for 10230 RDF triplets). More information on VantagePoint (online tutorial, example source code, etc) can be obtained from [12].

5 Conclusion and future work

The VantagePoint environment fills a niche that is not supported by the available ontology development tools. It offers an interactive visual user interface enabling developers to easily model the smart home environment and relevant services and applications.

The tool makes it possible to view ontology instances associated with complex contextual information in a more illustrative and understandable way. Moreover, we believe that the research presented is a step forwards providing a better understanding and wider acceptance of semantic technologies also for non-Internet services.

As for the future work, shortly we are planning to publish VantagePoint as Open Source Software. This will require some further improvements in its modular structure, which we facilitate the research and development community with in a means to extending the tool with new useful features and plug-ins including visualisation libraries, several more application domains support, tracing capabilities, etc. We have also some further ideas and work in progress towards the integration of dynamic features into the VantagePoint environment. These will mean that context events may come from real world sources (i.e. sensors) and also the semantic service register can be updated based on real world information. Thus the simulation environment will be even more realistic for the application developer and can also be used as the monitoring and management tool for some particular home applications.

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PUBLICATION III

Ontology driven data mining and information visualization for the networked home

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Ontology driven data mining and information visualization for the networked home

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***Abstract*—Data mining is the process of extracting hidden knowledge from data. As more data is gathered, data mining is becoming an increasingly important tool to transform this data into information. Visualization is central to data mining. Information visualization is the process of turning abstract data into a visual shape easily understood by the user, making it possible for him/her to generate new knowledge about the relations between the data. Ontologies represent a shared meaning of a domain and they can be used to describe almost any kind of domain concepts explicitly including their terms, attributes, values and relationships facilitating the communication between people and application systems. Leveraging the power of semantic technologies, ontology based data mining and recent trends in information visualization, this work presents the approach towards the management of multi-dimensional often temporal heterogeneous home data.**

Keywords-Intelligent home, data management, visualization

I. INTRODUCTION

Recent advances in pervasive computing, deployment of RFID devices and wireless sensors enable novel types of home services from various application domains such as e-health, assistive living, home monitoring and control. The examples of applications span from security and surveillance to monitoring of consumption of home resources (measuring, logging and comparing water and electricity consumptions) and status of appliances including their maintenance and history.

It is envisioned that future intelligent home will contain many more RFID-enabled and measuring technology embedded devices and systems for sensing several different physical phenomena and activities of the house. The vision when distributed services and devices all cooperate seamlessly with one another using information and intelligence to improve user experience are often referred as Ubiquitous computing and recently as Ambient Intelligence (AmI) [32][33].

Some time in the future AmI in the home, the office, the car, factory and mall will have matured. Sensing system will collect information accurately and reliably. AmI system will be able to respond to wind, rain and sun and people's most obvious daily needs such as lighting, indoor climate control and home maintenance task. AmI system will customize content and delivery modality. It will be able to start a day with playing music from preferred play list, favorite radio host, showing the personalized news or general summaries of hot news topics. It will be able to configure the program so that it follows the user everywhere in the house or, even in order to follow him/her in a mobile or portable device outside the home area. It will be able to download personal profiles and integrates game devices when friends are coming over to the user's house for interactive multi-player game sessions. It will be able set up video-conference sessions for people to watch TV together and share the newest acquisitions of their collections, or just communicate with each-other. Machine vision and face recognition systems will be able to detect the inception of anger, pleasure and boredom. Television will lower the volume when families fight and switch the channel when film is wearing thin. Washing machines will query our dirty clothes for washing instructions. Parents will no longer lose track of their children and adult relatives, when location and communication technology is sewn in their cloths. The information discovering, collection, processing and exchange will be the key factor in enabling of such scenarios. Obviously with growing amount of heterogeneous data generated in home, there is a growing need for integration of heterogeneous data sources and for inferring new knowledge from combined information to get the comprehensive view of the house.

Machine learning has received attention from the Artificial Intelligence (AI) community since '70s being applied in many real-world classification problems. During '80s, the term 'data mining' referred to machine learning techniques employed in knowledge discovery started appearing. Ambient Intelligence will engage AI techniques, and data mining in particular, even more, than it does now traditionally applied in industries such as banking, insurance, medicine, communication, and retailing to reduce costs, enhance research and increase sales. Discovering new knowledge, detection of astute patterns and associations from large amount of data will enable new type of scenarios beyond living spaces and buildings towards new ways of knowing and being informed.

For data mining to be effective, it is important to include the human in the data exploration process. The basic idea of

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visual data exploration is to present the data in some visual form, allowing the human to get insight into the data, draw conclusions, and directly interact with the data. Visual data mining techniques have proven to be of high value in exploratory data analysis and they also have a high potential for exploring large amounts of data. The visualizations of the data allow the user to gain insight into the data and come up with new hypotheses [34]. With recent advances in computer systems and graphics capability, the information visualization has become a hot research topic. On the same time the computer games industry has come up with new approaches for presenting data on computer screens in an illustrative and impressive way. It is succeeded in effectively exploiting different kinds of visualization techniques (isometric perspectives, 2D/3D views, spatial relations between objects, etc.). Nowadays many of the approaches implemented for educational or scientific purposes are inspired by computer games. Thinking visually in three dimensions benefits the sense of wonder and user interaction connected with the application of scientific and information visualization technologies [35]. Interactive visualization and interactive graphics may directly portray the description of the data or present the content of the data in a completely innovative form facilitating zooming, filtering, and finally obtaining details on demand.

However advances in visualization are not yet the part of intelligent home technology. The user interfaces available today are graphically simple however technically quit complex. Moreover there are too many control systems in the house with own control nodes and dedicated user interface. Effective aggregative visual interface would enable user to observe, manipulate, and understand the state of the house, and interact with data letting the user query information in real time.

On the other hand, due to diversity of applications and services related to home domain, it is unlikely that all of the knowledge can be represented with single software framework. The emergence of semantic web and the supporting technologies such as XML and OWL/RDF offers a promise to facilitate organization of heterogeneous knowledge. Ontologies developed first in AI field have gained wide popularity in the early 1990s to facilitate knowledge sharing and reuse in various application domain such as natural language processing and knowledge engineering. Since then, ontologies have extended to other research fields such as knowledge management, information retrieval, electronic commerce, medicine and natural science. The term ontology in philosophy refers to the theory about nature of existence while in computer science it is referring to all the core domain concepts, their relations, attributes and values. Ontologies have become increasingly popular because they promise a shared and common understanding of knowledge domain. Ontologies can describe explicitly the content and semantics of heterogeneous data sources to support integration, processing and further new knowledge discovering tasks.

The objective of this paper is to discuss further the technologies enabling aggregation of heterogeneous data source and facilitating data mining techniques applied to home applications, to present scenarios and use case which benefit from data mining, to discuss the importance of visualization aspects in networked home domain, and also to demonstrate some managing and visualization ideas and concepts through the prototype developed.

The rest of the chapter is organized as follows. Recent background technologies emerged facilitating integration of heterogeneous data sources, inferring techniques and visualization support are discussed next. The VantagePoint application empowered by discussed technologies and several use cases developed to demonstrate the benefits of data mining and visualization are presented in the following section. Last sections conclude with aspects of future work and future research directions driving by demand of future Ambient Intelligent landscapes.

II. Background Technologies

Inspired by Semantic Web, ontology languages such as Web Ontology Language (OWL) [1] ontology based technologies and tools have gained much attention recently in particular to represent and effectively query the diverse heterogeneous data types found in home [15][17][20]. Ontology based data representation allows to describe home contexts semantically and share common understanding of the structure of contexts among users, devices, and services. Semantic models enable a formal analysis of the home domain knowledge, such as performing data reasoning and decision making.

Numerous freeware and commercial tools to support the development and use of ontologies are currently available. Examples of ontology editors are: SWOOP (Mindswap, 2004) is a hypermedia-based featherweight OWL ontology editor; Protégé is a free, open source ontology editor and knowledge-base framework; TopBraid Composer™ [21] is an enterprise-class platform. The Application Programming Interfaces (APIs) for ontology languages provide programming language dependent means to load ontologies, manipulate the ontology classes and relations, perform reasoning, and provide persistent storage for the model. Jena [2] is the most popular open source Java frameworks to build semantics based applications. It provides the application developer with programming language level support for working with ontologies. The Jena inference subsystem is designed to allow a range of inference engines or reasoners to be plugged into it. Examples of such are FaCT++, Pellet, RacerPro. Such engines are used to derive additional RDF assertions which are entailed from some base RDF together with any optional ontology information and the axioms and rules associated with the reasoner. The primary use of this mechanism is to support the use of languages such as RDFS and OWL which allow additional facts to be inferred from instance data and class descriptions. These tools both help in ontology testing and in developing SW application level intelligence providing inferring and data mining capabilities for ontology applications offering either a language dependent API or the DIG interface.

While advancement in these tools has greatly improved the ability to test the ontologies and to build semantic applications with inferring support, these tools are not well suited for understanding the semantic relations in a complex multi-dimensional physical world environments such as dynamic networked home. The difficulty in designing and implementing of such environments lies in complexity of relations between the produced data and contextual physical properties of an environment such as available services and devices, their absolute and relative location, persons, their preferences and intentions. Different formal models, logical rules and hypothesises can be used to represent these relations and infer on new facts and states in progress. New knowledge discovery and fusion of information from sensor data with information from variety of other environmental observations can assist to detect anomalous behaviour of various process and home environment as a whole.

A. Visualization

Visualization links the two most powerful information processing tools known – the human mind and the modern computer. Visualization is a process in which data, information and knowledge are transformed into a visual form exploiting people's natural strengths in rapid visual pattern recognition [36]. Effective visual interfaces enable us to observe, manipulate, search, navigate, explore, filter, discover, understand, and interact with data far more rapidly and far more effectively to discover hidden patterns and come up with new hypotheses [37].

There are a number of classifications to categorize the diverse ways to use computer graphics, and the first classification is by the type (dimensionality) of object to be presented and the kind of picture to be produced. The pictures can be purely symbolic (2D graphs) or realistic (representations of real objects) [38]. 2D views are usually considered better for seeing the details of a particular part and navigating or measuring distances precisely, whereas three-dimensional displays are said to be good for gaining an overview of a 3D space, understanding a 3D shape, and navigating approximately in 3D [39][40]. Users also prefer 3D displays simply because of their familiarity and easy feel. With a 3D display necessary information is readily available and easily interpretable.

Which visualization type should be used depends on the problem domain. Different styles are effective for different situations. For example, the visualization of intelligent home environment requires that contextual information and spatial relationships are presented effectively in the visualization [10]. In addition, the visualization should be realistic, as realism breeds the expectation of accuracy, reliability and authority in the representation, especially when considering computer visualizations which aspire to simulate real environments. Therefore, for example the traditional graph visualization algorithms that are mainly focused on representing the abstract relationships between classes are not considered to be the best possible solutions for this particular problem domain [10].

In recent years the rapid development of computer game graphics has had a huge influence on visualization. The computer games industry has come up with new approaches presenting data on computer screens in an illustrative and impressive way and succeeded in effectively exploiting different kinds of visualization techniques. The rapid financial growth of the computer games market has made it the driving force in the development of consumer graphics applications and hardware.

Characteristic of many computer games is that the user is much more than an observer just watching the details of a visualized world. The possibility to interact with the visualized data enables user to gain a better understanding of it and multiple methods of creating interaction between the user and the graphical presentation have been established. In interactive visualization two kinds of dynamics can be identified: motion dynamics and update dynamics. With motion dynamics objects can be moved and rotated with respect to a stationary observer or the objects can remain stationary and the viewer can move around them, select the portion in view and zoom in or out for more or less detail. Update dynamics refers to an actual change of shape, position, or other properties of the objects being viewed. The ability to edit selected values, or to change parameters, resolution or representation, and to see their effects provides the possibility to present "what-if" questions and helps users to understand the data and to test different scenarios.

During the recent years the amount of data stored by computer systems has increased dramatically. Data is often recorded, captured, and stored automatically via sensors and monitoring systems. For example, in intelligent homes environment embedded sensors provide frequently data of such measurements of physical variables as temperature or lighting. While ontology enabled reasoning and data mining provide means to extract this data, the resulting visualized models can still be quite complex. How to effectively visualize the relevant dependencies and possible patterns detected in the data is one the biggest visualization challenges of today. Another challenge, closely related to the previous one, is to consider how to provide better interaction methods to the user The implementation of different interaction techniques such as filtering, zooming, and linking, thus allowing users to interact directly with a visualization, determine in many respects the value of the visualization system as interaction is, for many users, the Holy Grail of information visualization.

Inspired and taking benefits of identified trends and technologies and addressing the above discussed challenges and needs we have extended early developed home simulator named Vantage Point [31] towards the conceptual prototype to manage the heterogeneous home data.

III. VANTAGEPOINT TOWARDS AN INTERACTIVE DATA MINING

VantagePoint is a Java application that is able to visualize, query and edit semantic contextual information described in Web Ontology Language using Jena Semantic Web framework. Vantage Point provides a possibility to build contextual models of different environments without requiring any particular knowledge of semantic technologies such as ontologies. Through simple graphical operations users are able to create and edit the semantic context models and thus simulate virtual or existing environments. By populating the models with illustrative 3D icons, the different objects can be concretized and located in their exact positions. The semantic context models created with Vantage Point are saved as OWL files that can be used by applications or published as context sources for more dynamic use.

A. Visualization in VantagePoint

Vantage Point provides three distinct views to the visualized context model: the text view, the edit view and the isometric view (see Figure 1). The text view shows the semantic model in a textual form and it enables to examine how the changes made in the visualizations have affected the model. The edit view is a 2D 'ground plan' view of the environment that has been visualized, whereas the isometric view visualizes ontologically described environment more impressively from a three-dimensional perspective. The purpose of the two-dimensional edit view is to enable more accurate editing operations. In general, 2D views are considered better for navigating and measuring distances precisely, establishing precise relationships and performing spatial positioning [3][4]. The isometric view visualizes semantic information in a more impressive way and provides a better general view of the contextual environment. It is stated that by using the isometric projection, spatial relationships between objects can be seen within wide environments. Furthermore, the isometric projection has proven its effectiveness in visualizing three dimensional spaces in such popular computer games as 'The Sims' [6] and 'SimCity' [7].

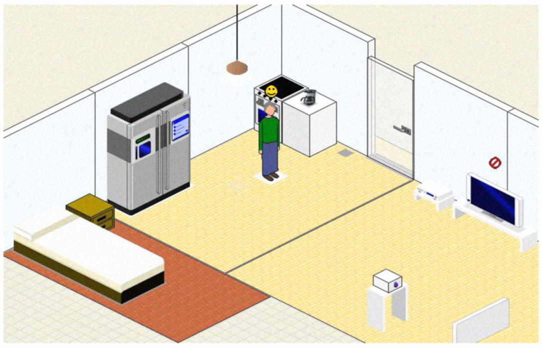

Figure 1. The isometric view of VantagePoint

The visualization in VantagePoint is based on Model-View-Controller (MVC) framework, which is a widely used architectural approach for interactive applications. It divides functionality between objects involved in maintaining and presenting data to minimize the degree of coupling between the objects [8]. In the Model-View-Controller architecture, objects of different classes take over the operations related to the application domain (the model), the display of the application's state (the view), and the user interaction with the model and the view (the controller) [9]. The structure of the Model-View-Controller architecture is presented in Figure 2.

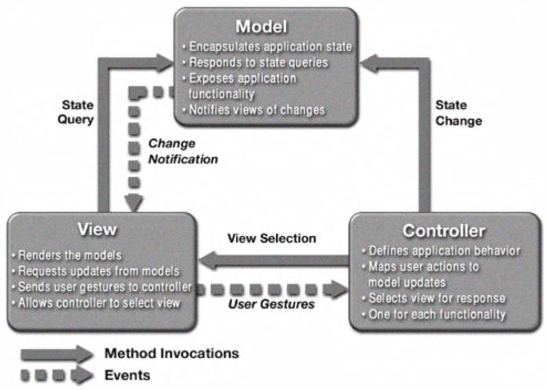

Figure 2. The Model-View-Controller architecture [9]

B. The Context Taxonomy

As discussed before, VantagePoint forms semantic models of different environments and visualizes them. More specifically, VantagePoint reads OWL files and searches for individuals that belong to a predefined VisualComponent class. Only individuals that belong to the VisualComponent class are visualized, all other data that is irrelevant or impossible to visualize are ignored. The VisualComponent class is divided into two separate subclasses - Item and Area. All things visualized fall into these two classes. If the ontology does not contain the class VisualComponent, only the text view is created and the user can make queries to it. The context of the VantagePoint world is defined in an ontology called 'VantagePoint.owl', which holds the class and property definitions of that context. Figure 3 presents the structure of the VantagePoint context model.

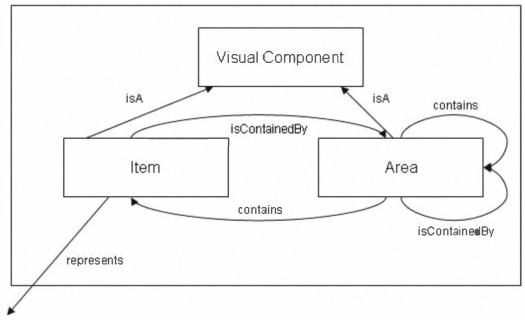

Figure 3. VantagePoint context model

VantagePoint provides also some interactive visualization features for the user. For example, such manipulation operations as removing, adding, moving and rotating of instances are supported. Each time a graphical editing operation is performed in some of the views, the semantic model is updated accordingly. For example, when the user moves an instance to another position in the visualization, the instance's location properties are changed and the 'contains' property is automatically calculated from the new location of the moved instance. When the user removes an area from the visualization, VantagePoint automatically removes all the instances that were contained by this area.

To facilitate heterogeneous home data integration for the further data mining and visualization we construct the ontology based data base, which is linked to the Vantage Point context ontology. The constructed ontology currently include the semantic representations related to sensor data (properties, measurement capabilities, etc), user personal information (profile, preferences, etc), and services deployed in the house.The library models are OWL ontology files that contain subclasses or instances of Areas (e.g. rooms or conceptual areas) or Items (e.g. devices, persons or furniture). Usually this sub-classing is provided by a modified local copy of the contextual ontologies used in the library. The ontology classes in library can have any amount associated semantic information (e.g. semantic descriptions of services provided by a device, reports, notes, user profiles) and may have relations to external semantic descriptions. The desired semantic descriptions can be imported into VantagePoint model to be further used for data mining and querying. Various tools such as Protégé can be used to create and edit such information. Any available ontology helping to model of various aspects of home environment can be reused and imported to Vantage Point for further processing.

C. *Case Studies*

AmIE (Ambient Intelligence for the Elderly) is an international ITEA project with various partners involved from four European countries, http://www.amieproject.com/. The main goal of AmIE project is the development and testing of a complete intelligent, distributed service system whose target is to improve the quality of life for the elderly [11]. AmIE provides several interesting use cases for VantagePoint as there is a need first to design the living environment semantically modeling various aspect of elderly adult life and then instantiate it. By realistically representing the home environment elderly adults and also their relatives and nurses are, for example, able to remotely examine the current state of the elderly and the home.

Besides of modelling the static home environment, VantagePoint allows integrating additional data from various sources into a single contextual model. By visualizing this model, VantagePoint provides an access to a large amount of information by just examining the different views provided. In the following we present some use cases and ideas illustrating how VantagePoint can support integration and interactive visualization of various heterogeneous home data. The use cases are selected from several application domains such as general home maintenance and assisted living enabled by sensing technology and other means such as self-assessment questionnaires used to collect welfare profile data.

For the assisted living and healthcare monitoring, we have used real world scenarios, which have inspired us to experiment with different sensor systems. These scenarios involve, for example, a 75-year-old woman who lives in her own apartment. The current wellbeing of the elderly person is estimated by combining data from several sources, such as wearable sensors, environment sensors, wellness self-evaluations and health record information. The system stores some information, for example, from bed sensors to estimate the sleep quality, or how many times certain electrical appliances are used or different doors opened during the day. Mental wellbeing is analyzed through interactive games, such as memory games. The elderly person can give her own assessment on her current condition to the system by touching a corresponding smiley face with a special touch screen application. Additionally, a care taker or a family member can give their own opinions about the current condition of the person condition using the same method or by using a web or mobile phone service. This information together with sensor information described above is combined to indicate the current condition of the elderly person.

To address the elements introduced in the scenarios, we experimented with the data produced by different sensors. Two types of sensors have been integrated to the VantagePoint context models: SimuContext sensors [13] and Carerider bed sensors. As we do not have much of real sensors to verify our developments and concepts, SimuContext tool helped us to simulate ones. These simulated context sources emulate the behaviour of life context sources. SimuContext enables the creation of virtual sensors of various kinds that are abstracted as context data producing entities. The virtual sensors generate context information with configured value and event models. Those models can be predefined values or generated randomly to model the un-deterministic behavior of the physical environment.

The SimuContext is lightweight, Java based and easily extendable, which makes it an attractive framework to be integrated with VantagePoint. The integration is carried out by allowing the adding of virtual SimuContext sensors into the VantagePoint context models and enabling users to configure and manage them through VantagePoint graphical user interface. We can imagine that in the future sensors and sensors embedding devices purchased from the nearest shop can be similarly integrated and controlled using VantagePoint interface. The data events produced by the sensors are stored into a separate semantic model and the data can be retrieved by utilizing the query and data mining operations of VantagePoint. In Figure 4 is presented an excerpt from an RDF-description of semantically stored SimuSensor data.


```
<rdf:Description rdf:about="http://vantagepoint.fi/owl/sensorDataOfTestHouse.owl#sensorEvent2">
 <rdf:type rdf:resource="http://vantagepoint.fi/owl/Sensor.owl#SensorEvent"/>
 <simuSensor:hasIntegerValue rdf:datatype="http://www.w3.org/2001/XMLSchema#string">19
          </simuSensor:hasIntegerValue>
 <sensor:hasTime rdf:datatype="http://www.w3.org/2001/XMLSchema#dateTime">0217T11:21:32Z
          </sensor:hasTime>
</rdf:Description>
<rdf:Description rdf:about="http://vantagepoint.fi/owl/sensorDataOfTestHouse.owl#sensorEvent1">
 <rdf:type rdf:resource="http://vantagepoint.fi/owl/Sensor.owl#SensorEvent"/>
 <simuSensor:hasIntegerValue rdf:datatype="http://www.w3.org/2001/XMLSchema#string">25
          </simuSensor:hasIntegerValue>
 <sensor:hasTime rdf:datatype="http://www.w3.org/2001/XMLSchema#dateTime">0217T11:21:31Z
          </sensor:hasTime>
</rdf:Description>
```


Figure 4. An example sensor data model

As can be noticed, the examination of the RDF sensor data models can be daunting and thus VantagePoint uses SPARQL [12] queries to extract the essential parts of the sensor information. In Figure 5 is presented an example query string, which returns the values and times of each sensor event that is stored in the sensor data model.

```
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
SELECT ?value ?time  WHERE
{
?e <http://vantagepoint.fi/owl/Sensor.owl#hasSensorEvent> ?r.
?r <http://vantagepoint.fi/owl/SimuContextSensor.owl#hasIntegerValue> ?value.
?r <http://vantagepoint.fi/owl/Sensor.owl#hasTime> ?time
}
```

Figure 5. A sensor data query

The parsed results of the sensor query can be seen in Figure 6. Experiments performed with simulated sensor's data have considerably facilitated our work for integration of real physical sensors, which is described next.

Query results for exampleSimusensor:

Time:	Value:
11:21:31	23
11:21:32	23
11:21:34	21
11:21:39	19
11:21:46	12
11:21:53	31

Figure 6. An example SimuContext sensor query result

As a real sensor system we have used the Carerider bed sensor manufactured by Audio Riders (http://www.audioriders.fi). The Carerider bed sensors allow collecting a versatile context data, such as the times an elderly person has got out of the bed during the night, or the respiratory frequency of the elderly. The data produced by the Carerider bed sensors is integrated with VantagePoint context model by uploading a file containing the raw sensor data from Audio Riders' web server, converting the data to a semantic form and storing it as a separate model.

The raw bed sensor data is stored in the Audio Riders' web server as a text file containing the sensor events collected over a period of 24 hours. Every bed sensor event contains such information as time of the event, state of the bed, activity level, breathing signal, estimated breathing frequency and acoustic pressure. Each sensor event constitutes one line of text in the data file and the different measurement values of an event are separated with a comma. The following example represents a small part of the raw sensor data file.

1224088318,1,0,43,0,0,0,-1,0,0,-1
1224088958,1,0,43,0,0,0,-1,0,0,-1
1224089598,1,0,43,0,0,0,-1,0,0,-1
1224090238,1,0,43,0,0,0,-1,0,0,-1
1224090878,1,0,43,0,0,0,-1,0,0,-1

Since the bed sensor provides numerous of events per every minute, the data file storing the raw sensor data is extremely large containing thousands of lines of text. To keep the required computer resources at a manageable level, the amount of data must be reduced before the sensor events are converted into a semantic form. The data extraction is carried out by selecting just one sensor event per each minute, which can be considered as an adequate accuracy for the purposes of VantagePoint. Additionally, VantagePoint removes the lines where the" state of bed" measurement value is "0", because there is no point to semantically store those sensor events when the bed is empty. However, an exception to this rule is the times when the person gets out of the bed but returns shortly afterwards because this kind of data provide valuable information about the possible sleeping disorders of the person.

Once, the noteworthy sensor events are extracted from the data, VantagePoint stores the event information line by line into a semantic model. Each sensor event is given a unique serial number and the measurement values are stored as property values of the events. In Figure 7 is presented a part of the Java code that extracts sensor values from the raw sensor data, annotates the values with metadata and finally, stores the sensor events into an RDF data model.

```
//the sensorData vector is examined line by line and events are stored in the model.
for(int i = 0; i < sensorData.size(); i++){

    bedSensorInd.addProperty(hasBedSensorEvent, bedSensorEventInd);

    Vector dataRow = (Vector)sensorData.get(i);

    bedSensorEventInd.addProperty(hasTime,
            bedSensorDataModel.createTypedLiteral(format.format((Date)dataRow.get(0)),
              "http://www.w3.org/2001/XMLSchema#dateTime"));

    bedSensorEventInd.addProperty(hasBedState,
            bedSensorDataModel.createTypedLiteral(dataRow.get(1),
              "http://www.w3.org/2001/XMLSchema#int"));

    bedSensorEventInd.addProperty(hasActivityLevel,
            bedSensorDataModel.createTypedLiteral(dataRow.get(2),
              "http://www.w3.org/2001/XMLSchema#int"));
```

Figure 7. A part of the Java code that handles raw sensor data

Finally, the sensor data model is attached to a bed instance held by a VantagePoint context model and the data can be accessed through queries etc. The results of the queries executed against the bed sensor data model can also be utilized when creating informative diagrams as can be seen in Figure 8. The middle side of the figure shows a part of the original query results and on the right it is shown the created diagram. The visualization of the bed instance holding the bed sensor data is represented on the left side of the Figure 8.

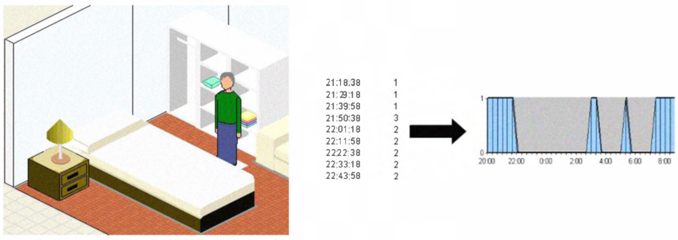

Figure 8. Query results and a created diagram

In order to semantically store different kind of sensor data, a new ontology level taxonomy was needed. The taxonomy for semantically storing sensor data is sketched in Figure 9.

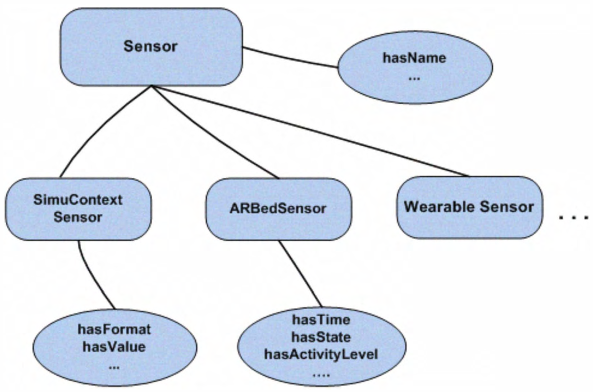

Figure 9. The sensor taxonomy

As presented in Figure 9, the sensor taxonomy contains the 'Sensor' main class and one sub class for each sensor type. The 'Sensor' class holds properties that are common to all sensor types and additionally, each sub class holds its own sensor type specific properties. For example, the 'hasName' property is common to all sensor types, whereas the 'hasSensorConfigFile' property is a 'SimuContext' sensor specific property. The sensor taxonomy is linked to the VantagePoint context taxonomy by defining the 'Sensor' class as a subclass of the 'Item' class.

In the AmIE, special touch screens are delivered to a group of test elderly people, who are expected to answer daily to the self-assessment questions shown on the screens. The questions are related to various aspects of aged adult life such as independence, safety, loneliness, etc. The daily questions can be utilized to assess the current state of the elderly. By analyzing the history of such answers some supportive actions towards the better quality of life for elderly adult is made. The information collected from bed sensors, questionnaires and other means available in the future can be utilized by elderly itself, relatives and care givers to obtain quick comprehensive view about how elderly is doing day by day. The state can be visualized in VantagePoint with certain status symbols, as presented for instance in Figure 10.

Figure 10. The state of mind – symbolic indication

VantagePoint supports the storage of the query answers as well as the welfare profiles by allowing its integration with the context models. The integration can be carried out by uploading the self assessment answers from a web server and then attaching them to a persons held by a VantagePoint context model. Similarly, other information such as preferences, agenda, personal data, etc. can be linked to a VantagePoint person, thus increasing the amount of information provided by the context model and the visualization.

As earlier mentioned, one of the key feature of semantic knowledge processing and reasoning are logical rules, which infer new facts from existing data. Working further on data exploitation aspects, it was discovered that the lack of a rule system support severely limits the reasoning capabilities of VantagePoint. Thus VantagePoint was decided to be integrated with Context Aware Empowerment (CAEMP) framework created by a Belgian project partner Alcatel. CAEMP framework brings together rules, sensor information and user-defined concepts in one layered, possible distributed model [44].

The integration was started by mapping the VantagePoint ontologies and CAEMP rule system ontologies together, which enabled common understanding between the two applications. In this way, the instances created with Alcatel's rule system can be managed with VantagePoint and vice versa. One of the key actions in this ontology mapping was declaring the class 'ContextEntity' found in CAEMP ontology as equivalent class as VantagePoint's 'Item' class.

```
<rdf:Description rdf:about="http://www.caemp.com/caemp#ContextEntity">
  <owl:equivalentClass rdf:resource="http://vantagepoint.fi/owl/VantagePoint.owl#Item"/>
</rdf:Description>
```

Figure 11. The ontology mapping

Secondly, a remote repository for sharing context models and ontologies was established and also a web service to handle the context model and ontology sharing was implemented. As a result of this integration work both applications are able to share same context models, which enables VantagePoint to include rules in its context models and CAEMP framework to visualize its context models.

The CAEMP rules are defined as RDF statements, which make them difficult to understand for a user. Thus a rule visualization feature was implemented to VantagePoint, which extracts the semantic descriptions of the rules from the RDF models and visualizes them in a more comprehensible from. In Figure 12 is presented example rule visualization in which RDF statements that define a rule "IF a fridge door is left open THEN send an SMS message to Marc" is being graphically shown.

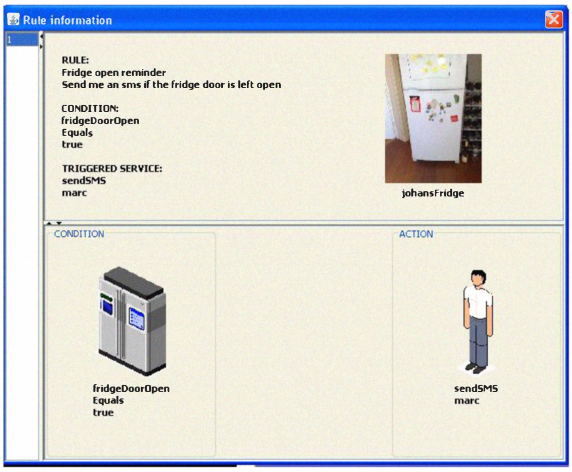

Figure 12. Rule visualization in VantagePoint

One of the most important features of VantagePoint is the ability to provide context information to nurses and relatives. Moreover, it is essential to enable this context data distribution also for smaller devices, such as mobile phones. Therefore, a development work is started, which aims to enable users to remotely receive VantagePoint context events into their Java supporting mobile devices. The implementation work is based on two existing OSGi [16] solutions: Concierge [42] and R-OSGi [43]. Consierge is a full implementation of the OSGi R3 specification and it is tailored especially to resource-constrained devices such as mobile phones. R-OSGi is a middleware platform that extends the centralized, industry-standard OSGi specification and facilitates the distribution for arbitrary OSGi framework implementations simplifying the development of distributed applications with no performance cost [43]. In our case R-OSGi enables the communication between VantagePoint and mobile devices over the web.

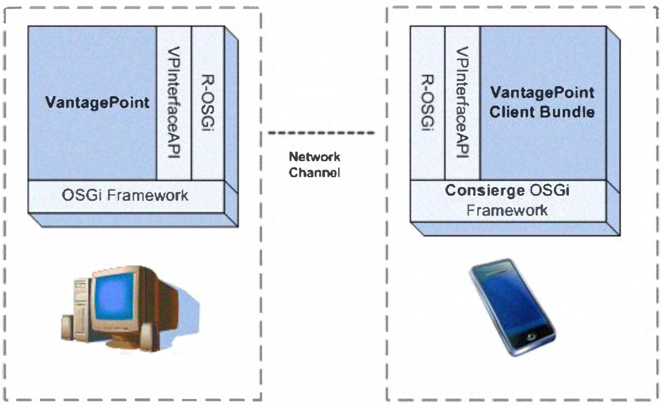

Figure 13. VantagePoint context data distribution through OSGi

In Figure 13 is presented how VantagePoint distributes context information to mobile devices. As can be seen both sides run their own OSGi framework installations and because of the resource constrains, the OSGi framework in the mobile device side is Consierge. The connection between the two frameworks is established by R-OSGi, which handles the data transfer between both sides. The bundle 'VPInterfaceAPI' defines the interface between VantagePoint and mobile devices. The Java implementation of the interface is shown in Figure 14.

```
package R_OSGi_interfaceAPI.interfaceAPI;
/**
 * VantagePoint R-OSGi interface.
 *
 * @author inilkka
 */
public interface ServiceInterface {

    public String getContextUpdate(String queryStatement);
    public String executeQuery(String queryStatement);

}
```

Figure 14. VantagePoint R-OSGi interface

At this moment the interface consists of just two methods 'getContextUpdate' and 'executeQuery'. With the first method the client can monitor the changes of some specific detail in the context model (e.g. the elderly is asleep or awake) and with the latter one the client can freely query any information about the context model held by VantagePoint. As a result of this implementation work relatives and care takers are able to remotely receive real time information about the current state of the home even if they are on the move. The next step of this implementation work is to enable a two-way communication between VantagePoint and mobile devices. In this way users could not only receive information, but also remotely manage the context models held by VantagePoint.

IV. FUTURE RESEARCH DIRECTIONS

Vision of ambient intelligence, ubiquitous computing and intelligent environments is evolving all a while integrating tiny microprocessors and sensors in everyday objects in order to make them 'smart'. The AI methods including data mining, ontology based reasoning, and inferring techniques is a basic building block of such vision ensuring the ability to combine different information sources in the backbone of any 'smart' system relied on the large variety of different sensor input. Leveraging recent developments in the AI field, 'smart' objects can sense their environment, monitor themselves, communicate to other 'smart' objects and interact with humans in a new and intuitive way.

Obviously benefits of sensing technology will not stop in designated places such as private home, cars and smart public spaces. They will go far beyond of living spaces and buildings facilitating a range of new applications, services and business models applied to industrial- and global economic processes. As more and more entities in the economic processes, such as goods, factories and vehicles will being enhanced with methods of embedded sensing, monitoring and information exchange, the whole life cycle of products from the birth of their components to their complete consumption and recycling can be verified in real time. Thus inventory management may benefit from accurate, real-time information on location and condition of goods, equipment and manpower. The critical product parameters (e.g. temperature-sensitive goods such as chemicals or groceries) can be constantly monitored by tiny wireless sensors. Equipped with communications capabilities, such goods can communicate relevant parameters to the outside world and trigger the alarm in the event of excessive temperature of the container, being in transit. Alternatively, the goods may also attempt to take corrective actions by controlling the temperature of the container. Invisible tags embedded in products will allow consumer devices to access the object's virtual representation (ingredients, product review, etc) as well as direct links to online or real-world shops selling this item. Goods could not only talk about their prices, ingredients and availability, but also provide a detailed history on their production, use and repair [41].

Such real-time economy and its new applications and services will engage the AI and data mining in particular for further technological developments and innovations in the area of scaling data collection, accurate and fast searching and information combining techniques, ontological interoperability and light low-memory consuming inferring mechanisms to guarantee the reliability, manageability and control over built intelligent economic landscapes.

Moreover visual exploration also needs to be tightly integrated with the systems used to manage the vast amounts of relational and semi-structured information, including database management and data warehouse systems. Last but not least, the sophisticated data mining algorithms should be combined with the intuitive power of the human mind. The complexity of the visualization data can make analysis a challenging cognitive activity. The focus of most continuous model visualization research is on creating new and faster techniques for displaying data. However, in recent years, human factors in visualization design have gained increased attention from the research community, more attention should be paid to users who must view and manipulate the data because how humans perceive, think about, and interact with images will affect their understanding of information presented visually [39].

V. CONCLUSION

Data mining techniques will be a basic building block of future Ambient Intelligence landscapes, such as networked home of the future and beyond. An automated data collection would not be much use unless it was combined with powerful search, retrieval and inferring technology that allowed us to combine large amounts of data for very specific information. And the ability to combine different information sources, especially large, innocuous ones such as sleeping patterns, eating habits or usage history, is the backbone of any 'smart' system, which must make the best use of a large variety of different sensor input to take decisions that make it appear to understand what is happening around us.

This paper has presented the approach that supports the integration and interactive visualization of diverse heterogeneous home data. We believe that this tool will provide better possibilities for house residents, care takers and relatives to understand the intelligence embedded in the environment and supervise the home. By enabling the remote access to home data, users are given the ability to acquire home related information with mobile devices also when they are on the move. The capabilities of the tool are easily extendable and customizable. For example, new views can be added or new icons representing devices, furniture, persons, etc. can be drawn and added into the icon libraries of VantagePoint. Additionally, the OSGi interfaces can be extended to better serve the needs of different types of client applications.

The tool has been offered for testing to researchers within VTT and also to partners within AmIE project consortium, and the feedback has been positive. As for the future work, we would like to improve semantic contextual models on which VantagePoint is built. More expressible ontological models will allow for better reasoning on home information, hereby facilitating comparison of data histories and empowering more sophisticated decisions. Also by developing the interactive visualization features of the tool, better possibilities to manage home environments can be provided. In this way users can, for example, not only visualize house related rules, but also modify them.

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PUBLICATION IV

Monitoring and Visualisation Approach for Collaboration Production Line Environments: A Case Study in Aircraft Assembly

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Monitoring and Visualisation Approach for Collaboration Production Line Environments: A Case Study in Aircraft Assembly

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Abstract

In this paper, the SPMonitor tool, which is designed to monitor and visualise run-time execution of productive processes, is proposed. SPMonitor enables the dynamic visualisation and monitoring of workflows running in a system. It displays versatile information about currently executed workflows, thus providing a better understanding of processes and the general functionality of the domain. Moreover, SPMonitor enhances cooperation between different stakeholders by offering extensive communication and problem-solving features that allow the actors concerned to react more efficiently to different anomalies that may occur during a workflow execution. The ideas discussed are validated through a real-life case study related to aircraft assembly lines.

Keywords: Collaboration, Productive Lines, Workflow, Monitoring, Visualisation.

1. INTRODUCTION

The field of computer-supported collaboration work is often associated with office work. However, industrial production lines such as products assembly lines are highly relevant as a case for this research field. Several issues are involved considering the complexity of products manufactured:

- In such processes, various teams with different areas of technical expertise are involved in activities to be performed synchronously. These activities are not always sequential.
- There is an increasing complexity of subsystems to assemble, along with the fact that supply components come from various industry parties and players.
- One activity in the process may influence another, therefore the coordination is required.
- There is heterogeneous information all over the shop floor and interdependencies exist within the information spaces.
- There are external factors impacting operational status, such as unavailable or multifunctional equipment, delay in supplier components or changes in the human resources involved.

In addition, tight deadlines and a reduction in the time-to-market place additional pressure on the organisation and monitoring of working processes towards their productivity and the quality of the final product.

The design and development of modelling and analytical techniques of the production lines was the subject of extensive study in the past. The use of commercial digital mock-up systems (DMU) enabling different visual qualities and functions are becoming more common [1][2][3]. However, effective real-time progress monitoring tools supporting DMUs are still immature.

The complexity of modern production lines and the dynamic nature of the domain make it difficult to maintain the ‘As-Planned’ progress during the actual execution (e.g. discrepancies and frequent changes). This results in schedule and cost overruns, which accordingly call for the efficient monitoring and coordinating interfaces with the production process, which is able to provide a real-time view of the current state of processes and relevant attributes (‘As-Is’ view).

Existing coordination solutions developed and reported in the literature so far are mainly based on public interactive displays. The andon system [4] made famous by Toyota is simply a way of reporting the occurrence of a problem on the assembly line (‘andon’ is the Japanese for ‘signal’). In case of a problem, the operator pulls an alarm cord and an electronic board is activated. Early projects, such as LiveBoard [5], focused on supporting collaborative activities through large electronic whiteboards using novel interaction techniques. Later on, this work was extended in recent projects by embedding several interconnected displays in the environment to support more complex collaboration activities, including Trauma’s center Whiteboard [6] iLand [7] and iRoom [8]. From an application point of view, the closest to our research is a study presented by [9] targeting user acceptance issues in the environment composed of large public displays to facilitate the collaborative process in the aircraft final assembly lines in Toulouse. There are also other applications that have exploited large displays to make information on activities available to a community of users.

These systems are developed with the objective of supporting a broad spectrum of group activities, creating a common information space and providing the background awareness on activities that a number of various groups/teams are involved in and tasks that have been accomplished. However, for a productive assembly project, as-built progress or DMU should be constantly monitored and compared with as-planned assembly progress, and real-time prompt corrective actions should be taken in case of observational discrepancies. Current tools such as graphs, charts and photos may not facilitate the communication of progress and ensure corrective action is taken clearly and quickly enough. More advanced means aiming at anticipating problems like overlaps of assembly parts and proposing corrective actions in an intuitive and promptly intelligible way are still lacking.

Based on the aspects discussed above and through the exploitation of the close cooperation with the EADS R&D team in the European Smart Products project [10], this paper presents a novel approach to support the collaboration of various actors involved in the processes related to production line environments.

Leveraging recent advances in semantic technologies, 3D visualisation techniques and contextual workflow modelling mechanisms, SPMonitor provides intuitive and convenient visual aids to support various actors involved in overall processes running on industrial production lines. By managing the interdependencies between numerous activities running concurrently, it aims to provide support for the combining, storage and distribution of various statuses, scheduling information, tasks, the usage of resources and tools, and updates providing contextual views to operators, support teams and managers responsible for the overall processes on the line. The combination of interaction means and interface elements to run-time environment and DMU facilitate the ability of the tool to quickly sort and display the performance metrics and deviations, possible unexpected events and anomalies in order to highlight the high priority requirements and actions required for recovering from errors and assembling resources.

In addition, from a scientific point of view, this research contributes with the novel approach of semantically annotated contextual workflow-based production process description. Semantically described workflows provide powerful reasoning potential to align information spaces of productive lines and enable richer visualisations showing comprehensive data in a single view. The ontologies used to describe workflows, environmental features and sensory perception devices can be flexibly extended. With new plug-in domain-specific ontologies, the tool can support additional application domains.

Moreover, the visualisation layer of semantically defined workflow descriptions supporting real-time progress monitoring is proposed. Various contextual views empowered by 3D functional graphic elements provide the value for the coordination and control of production lines. The visualisation libraries can be extended with domain-specific needs.

This paper is divided into six sections. Section 2 presents the background of the application domain for our study and the most important requirements that guided the development of the SPMonitor. Section 3 details the design and implementation of the tool. The run-time execution of SPMonitor and experiments that were accomplished to validate the prototype are described in Section 4. Section 5 provides the initial evaluation results performed by researchers and domain experts to measure the usability and perceived usefulness of the tool. Finally, Section 6 presents the conclusions drawn from the research project.

2. CONTEXT AND REQUIREMENTS

On an aeronautical final assembly line, the aircraft goes through several stages before completion. The process is often not sequential: several operator teams can be involved at the assembly station. Apart from operators performing assembly tasks, there are also support teams and a manager. The support teams help operators to solve operational problems and verify the technical issues, deal with logistics and ensure that the necessary tools are available for operators. The manager is responsible for the overall process of assembly and is also able to take action in cases where discrepancies are detected. Paper-based coordination between various actors is still used on the lines. Operators facing a problem or needing to validate an operation have to walk over to the support offices, write a report and verbally notify the appropriate support person. This all takes time.

In our context, the realistic scenario provided by EADS for research purposes involves two operators who have received a work order to tighten two electric harnesses onto an aircraft panel. Both operators work simultaneously on the same work order, which may contain several sub-tasks. The operators are also equipped with tools, a nomadic device and a smart tool (e.g. a smart rivet gun, a smart glue gun or a screwdriver). The nomadic device guides the worker through the workflow and the smart tool is used to tighten assemblies. The scenario also includes a support team that monitors the assembly procedure remotely and reacts in case of unexpected events during the process, and a station manager who is in charge of the overall organisation of the assembly line. More information about the background to the scenario can be found in [11] [12].

The main purpose of SPMonitor is to support cooperation between different actors in the scenario. First of all it should provide better understanding about work processes by representing an up-to-date visualisation of the current state of the assembly process. Besides visualising work processes, SPMonitor should be able to show illustratively the possible anomalies that may occur during a workflow execution and help the support team to react more efficiently to the problems. Moreover, SPMonitor is supposed to be used as a collaborative tool to exchange information between operators and the support team when resolving anomalies. Finally, SPMonitor can be utilised in the subsequent diagnosis, in which the support team and the station manager analyse the workflow performance data and any possible anomalies in cooperation.

3. DESIGN AND IMPLEMENTATION

Based on the context and requirements discussed previously, an approach that supports the collaborative visualisation of assembly processes was built. SPMonitor contains three main building blocks: a workflow management system, communication middleware and monitor software. The role of the workflow management system is to manage and execute processes and provide the necessary information for external applications. The communication middleware intermediates, either remotely or locally, between data from different components, and finally, the monitor software implements functionalities required for workflow monitoring. Figure 1 represents the compositional structure in more detail.

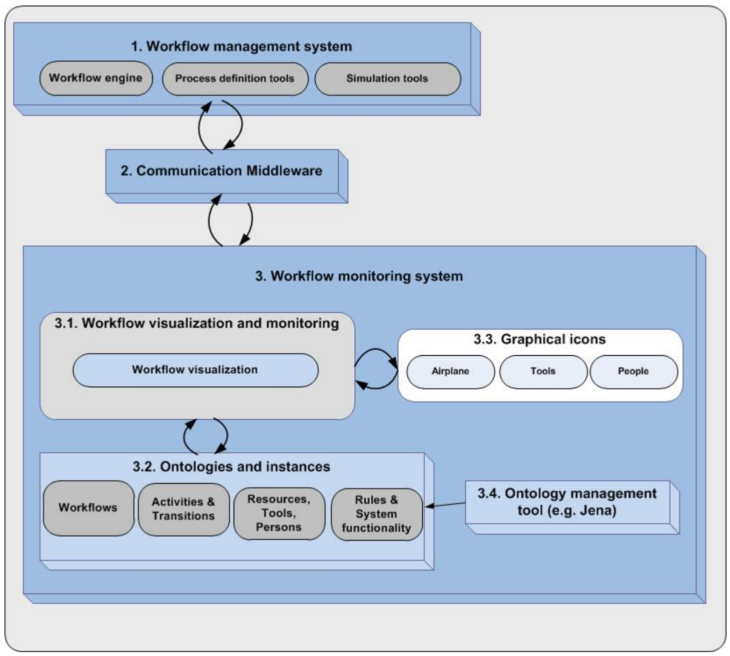

FIGURE 1: FMC block diagram of the SPMonitor components

The different components are described below in more detail:

- **Workflow management system** contains software tools for designing, defining and executing workflows. Additionally, it provides the necessary data for workflow monitoring using publish/subscribe mechanisms, for example.
- **Communication middleware (API)** acts as an intermediary between workflow management and monitoring systems. Moreover, it provides a means to remotely discover different components in the line system. Mundocore middleware [17] is used to provide the communication infrastructure for the information exchange in the line.
- The **workflow monitoring system** realises the different functionalities needed for semantically modelling and visualising different processes and reacting to anomalies. The main parts of the workflow monitoring system:
  - **Workflow visualisation and monitoring** is a core component of the system. It provides mechanisms for visualising workflows and other related information, as well as possible anomalies. Additionally, it implements the different interactive elements needed, for example, for managing anomalies.
    - The **ontologies and instances** component is a semantic library represented by ontologies which contains a workflow-related knowledge base. This component hosts the semantically

modelled workflow descriptions that are visualised with the monitor tool. It may also contain other semantically modelled information, such as rules and data describing different resources that are associated with workflow activities.

- **Graphical Icons** provide visualisation libraries containing domain-specific 3D icons that are used in workflow visualisations
- The **ontology management tool** allows querying and updating ontology instances.

3.1 Semantic Workflow Data Model

One of the requirements that arose in the scenario was enabling the integration of heterogeneous workflow-related information into a single data model, which in turn facilitates more sophisticated data analysis and diagnostics capabilities through automatic reasoning and richer query opportunities, for example. The diverse work process data includes information such as activities, transitions, resources (e.g. people, tools), restrictions (e.g. deadlines, required skill levels) and preconditions. Semantic technologies play an important role in realising this requirement as they allow describing workflow activities, transitions and resources in a semantically rich form, and additionally, they provide powerful reasoning potential [29]. The data fusion capabilities also enrich the visualisations because the integration of data from multiple sources increases the amount of available workflow information, thus leading to more comprehensive visual representations.

As explained above, SPMonitor acquires non-semantic workflow information from a workflow engine and converts it into semantic form. Currently there are several [20][21][22] usually domain dependent approaches that define ontologies for semantically describing workflows. Moreover [19] defines a semantic workflow language OWL-WS (OWL for Workflow and Services) and a specific semantic workflow representation model for describing dynamic work processes that also enable the specification of higher-order workflows.

However, for this study it was decided to design a new workflow ontology that adopts some elements from the existing approaches but is especially adapted and optimised for visualisation and monitoring purposes. This more lightweight and flexible ontology is unencumbered by the burden of providing a means for workflow task processing. On the other hand, the defined ontology structure offers enough expressiveness to allow for the performing of sophisticated diagnosis and analysis operations. Additionally, the workflow ontology is general enough to be able to address various problem domains. The specified ontology was influenced by our earlier work on designing expandable ontologies for facilitating heterogeneous data integration for data mining and visualisation purposes [24].

The ontology specified in this study defines concepts, relationships and attributes needed for describing workflows and other related information. This workflow ontology holds the class and property definitions of the entities that the SPMonitor workflow models are built on. The class hierarchy of the workflow ontology is presented in Figure 2.

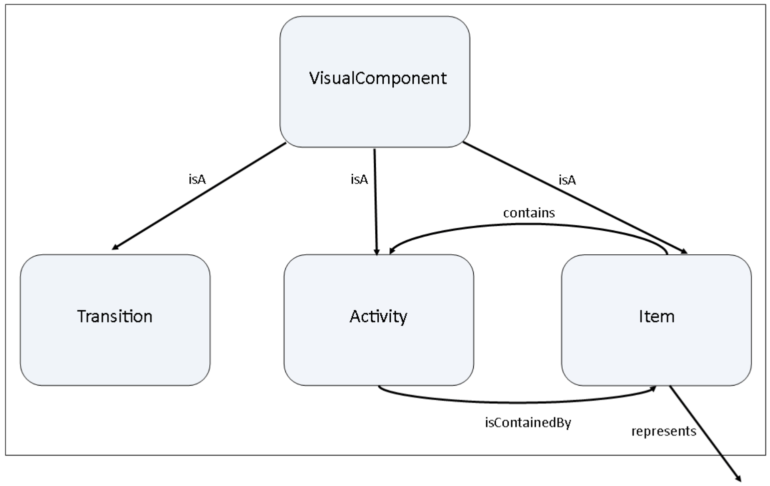

FIGURE 2: Context taxonomy

The main class of the workflow ontology is ‘VisualComponent’, which is divided into three subclasses – ‘Transition’, ‘Activity’ and ‘Item’. The class ‘Transition’ represents transitions that link different activities together. For each transition an ID, a source activity and a destination activity must be determined. Additionally, a transition may have a type property, which describes the type of relationship between source and destination activities. Possible type values for transition are “otherwise”, “condition”, “default exception” and “exception”. The class ‘Activity’ represents different steps or tasks of a workflow. Each activity instance defines its own ID and state values. The possible state values for activities are “not started”, “open - running” and “closed – completed”. Moreover, an activity may hold some additional properties such as resource requirements or time constraints. The third sub-class, ‘Item”, refers to entities that are contained by an activity. A typical item may be an operator that is assigned to a certain activity. Items may also have their own property values describing them in more detail.

SPMonitor forms semantic descriptions of workflows according to the ontology presented above. These models are dynamically updated each time a workflow management system sends an event message informing of activity state changes or anomaly occurrences, for example. The semantic workflow models are saved as OWL [23] files that can be used by other applications or opened with SPMonitor to be visualised or analysed later. Although the presented ontology is quite concise, its true power resides in its expandability. The ontology can be extended by integrating “plug-in” ontologies into it. This can be carried out through sub-classing or mapping concepts together with the ‘owl:sameAs’ statement, for example. With these plug-in ontologies, the tool can be adapted to support multiple different problem domains or integrated with other existing workflow ontology definitions.

3.2 Interactive Visualisation

The support for the enhanced understanding of work processes was released by designing illustrative and transparent workflow visualisation views that give a good overall representation of the data, and also provide the opportunity to acquire more detailed information on demand. Effective visualisation approaches enable humans to observe, manipulate, search, navigate, explore, filter, discover, understand and interact with data rapidly and effectively, to discover hidden patterns [30][31]. Moreover, interactive visualisation allows for the examination of the presentation of data on the fly from different perspectives and angles, helping the end user to understand the results of analysis and information retrieval better [13]. Thus, the different visualisation schemes were implemented to allow users to see various aspects of monitored workflows with different levels of abstraction and to interact extensively with the data being visualised.

The visualisation of workflows in SPMonitor is based on the Model-View-Controller (MVC) framework, which is a widely used architectural approach for interactive applications. The framework is successfully utilised earlier in the interactive visualisation of semantic context data, for example [25]. The Model-View-Controller framework divides functionality between objects involved in maintaining and presenting data to minimise the degree of coupling between the objects [14]. In the Model-View-Controller architecture, objects of different classes take over the operations related to the application domain (the model), the display of the application's state (the view), and the user interaction with the model and the view (the controller) [15].

The modularity of components has enormous benefits, especially when building interactive applications. Isolating functional units from each other as much as possible makes it easier to understand and modify each particular unit, without having to know everything about the other units. This three-way division of an application entails separating the parts that represent the model of the underlying application domain from the way the model is presented to the user and from the way the user interacts with it [15].

SPMonitor presents a novel way of visualising semantically defined workflow descriptions by providing four distinct views to examine models: a general view, a text view, a 2D view and an isometric view. In the following, each of the four views is described in more detail.

- **General view** gives a general picture of the overall situation. It shows the workflows that a currently active in a workflow management system and their current states.
- **TextView** provides a representation of a workflow model as it is written in OWL format. The view allows examining a workflow model in a textual form enabling also to discover the hidden workflow data that cannot be visually represented.
- **2DView** represents activities and transitions of a workflow in a “ground plan” like view. Activities are visualised as squares that are connected by transitions and the colour of the squares indicate the state of different activities. Similarly, the types of transitions are presented using colour codes. The purpose of the 2D view is to provide a better general insight of a workflow. In general, 2D views are considered better for navigating, establishing precise relationships and performing spatial positioning [16][17].
- **Isometric view** builds a visual representation of workflows from an isometric perspective. The visualisation provides a general picture of the monitored workflow and additionally it allows for the integration of varied workflow-related information within a single view perspective. For example, a visualisation of an activity defining an assembly task may include icons that represent the operator that is assigned to that activity or tools that are needed for executing the assembly task.

4. RUN-TIME EXECUTION

During the assembly process where several working processes are running in the background, a support team may examine the situation and select a workflow to be monitored. SPMonitor acquires the necessary information from the workflow management system and forms a semantic model of that workflow. To enable the dynamic monitoring of a selected workflow, the workflow management system notifies SPMonitor of different changes in the workflow execution data. For example, each time a monitored workflow proceeds from one activity to the next, a notification is sent to SPMonitor and the views are updated accordingly. The sequence diagram shown in Figure 3 illustrates the monitoring of workflows with SPMonitor in more detail.

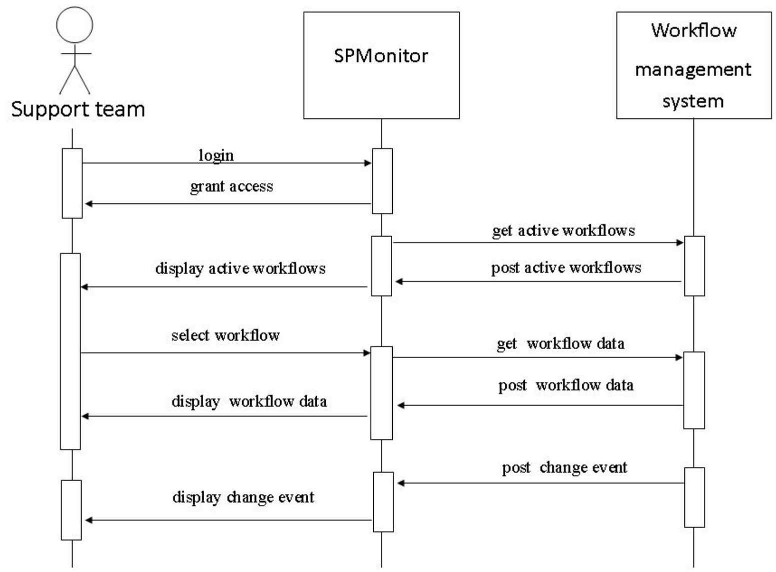

FIGURE 3: A sequence diagram of workflow monitoring

As previously discussed, SPMonitor contains three different views to visualise a single workflow. A graphical representation of the workflow model illustrates the different activities and transitions that are contained in the monitored workflow. The support team has also the opportunity to acquire additional information about a single activity by browsing for it. The opened information dialogue contains such information as work order name, operator performing task, state of activity, and possible sub-flow and sequence order of the selected activity. The status of different activities is indicated with the use of colours. The light blue colour means that the status of an activity is “not started”, a darker blue colour indicates that an activity is currently in the state “open - running” and the darkest blue shade symbolises the “closed – completed” state. Finally, if an activity is red, it means that an anomaly has occurred during the execution of that activity.

The different transitions are also indicated using colours. For example, a conditional transition is represented using yellow and an activity that is only entered in the case of an anomaly is interlinked with a red transition. If a transition does not have a type property, it is coloured grey. Figure 4 represents a screenshot from SPMonitor in which the workflow of the assembly case is visualised. The 2D view is shown in the upper panel and the isometric visualisation is represented in the lower part of the picture. As can be seen, the 2D view provides a more general picture of the monitored workflow, showing all the activities and transitions within a single view, whilst offering zoom in and zoom out functionalities. The isometric view represents a more detailed view of the workflow, populating different activities with icons that represent the operators and tools assigned to those activities.

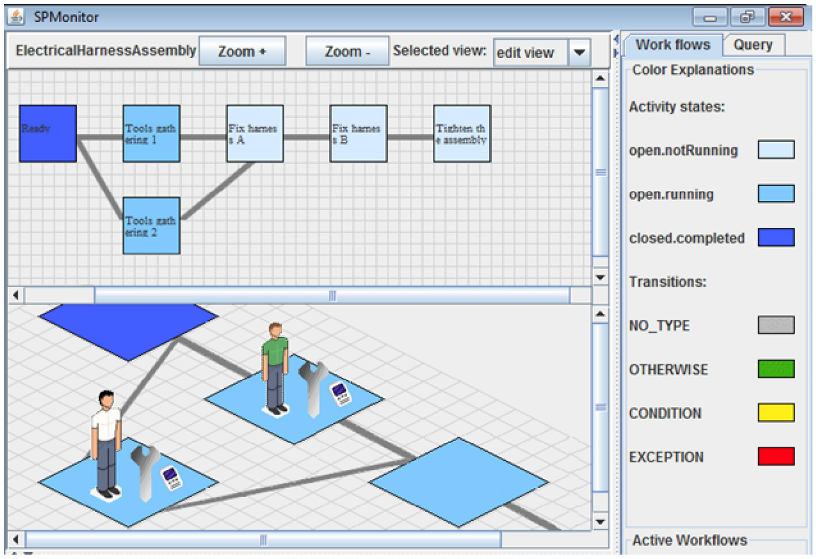

FIGURE 4: Visualisation views representing the monitored workflow

In the domain of aircraft manufacturing, work orders are often so complex that they cannot be expressed with single-level workflows and thus multi-level work processes must be utilised. In multi-level work processes, workflows contain activities that comprise a workflow of their own. These sub-workflows define the tasks that must be performed inside an individual main-workflow activity in order to complete it. Additionally, several operators may be assigned to a single workflow, which demands that activities are performed in parallel. In order to address these challenges, the functionalities of SPMonitor were designed to support the monitoring of workflows that include numerous of sub-workflows and various operators. For example, when a monitored workflow proceeds to an activity that launches a sub-workflow, SPMonitor automatically opens that sub-workflow to be monitored in a currently active visualisation view

4.1 The Management of Unexpected Events

An important part of the EADS scenario is the treatment of an unexpected event during the process. First, SPMonitor must dynamically inform the actors concerned about an occurrence of an anomaly and second, it must provide the means to recover from a problem situation. The sequence diagram presented in Figure 5 illustrates the interaction between SPMonitor and the support team in the scenario.

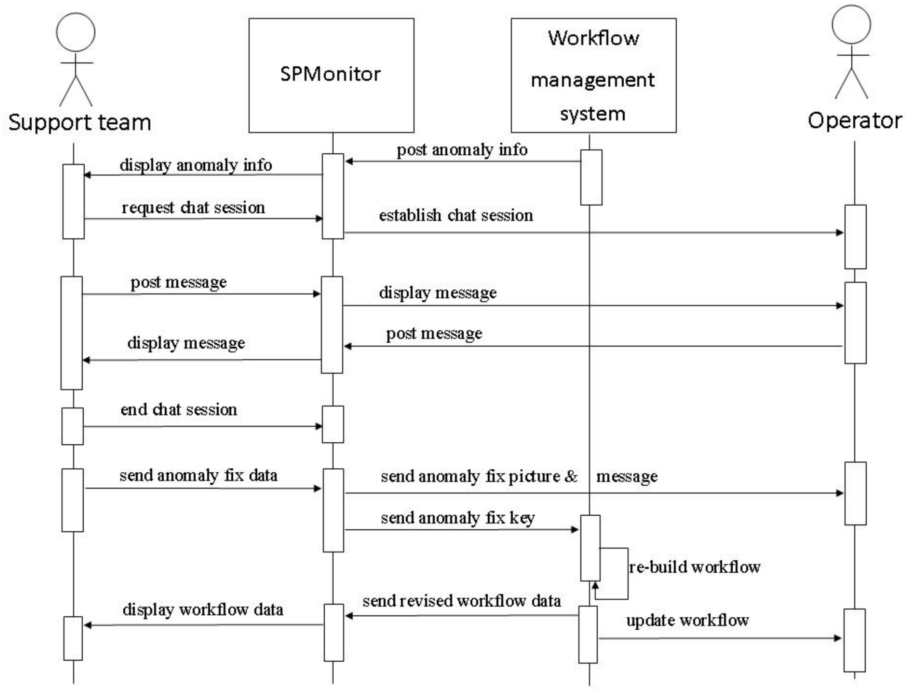

FIGURE 5: The sequence diagram for anomaly management

To facilitate the interaction between various actors involved, SPMonitor defines an interface element that enables the workflow engine to send a notification about unexpected events. The notification contains the necessary information for addressing different problems. Additionally, SPMonitor includes various communication features and problem-solving functionalities that assist users in managing unexpected events. For example, the support team is able to dynamically modify process definitions at run-time.

Any anomalies that occur are usually managed in cooperation with operators and a support team. SPMonitor enhances the cooperative work by disseminating information about anomalies and providing communication mechanisms to exchange data between employees. In the example scenario an operator notices that an earth wire is missing and thus decides to interrupt the procedure as it cannot be finished properly. The operator is also able to describe the problem in more detail by writing an anomaly message using the nomadic device.

In SPMonitor, the anomaly is indicated by representing the involved activity in red and opening an anomaly information dialogue. The anomaly information dialogue contains such necessary details about the unexpected event as the activity in which the anomaly occurred, a descriptive picture and the message that the operator has written. If the support team perceives that the data contained by the anomaly information dialogue is inadequate, it can start a chat session with the operator to acquire more details about the problem. SPMonitor establishes the chat connection with the operator’s PDA device by using a communication middleware solution.

Once the support team has enough information about the anomaly, it can decide how to proceed with the task orders. If the support team feels that the assembly process can be completed despite the anomaly, it can informally advise the operator on how to work around the problem and press the ‘Proceed’ button in the anomaly information dialogue. However, if the unexpected event prevents the workflow from proceeding, the support team can interrupt the workflow by pressing the ‘Stop workflow’ button. In this case, the support team will usually need to completely redesign the process definition with the workflow management system.

The final option is to dynamically redesign the workflow using the communication capabilities of SPMonitor. In that case, the support team defines a ‘fix key’ that indicates to the workflow management system how the problem can be resolved in run-time. Besides the fix key, the support team defines a descriptive picture and a textual message that guide the operator in solving the problem. The information is transmitted to the workflow management system that re-directs the descriptive picture and the message to the operator’s nomadic device and adds a complementary activity into the workflow. In this case, the new activity is called “Fix earth wire”. Subsequently, it notifies SPMonitor of the changes in the workflow so that the monitor visualisation can be updated. The data flows between the operators and the support team is illustrated in Figure 6.

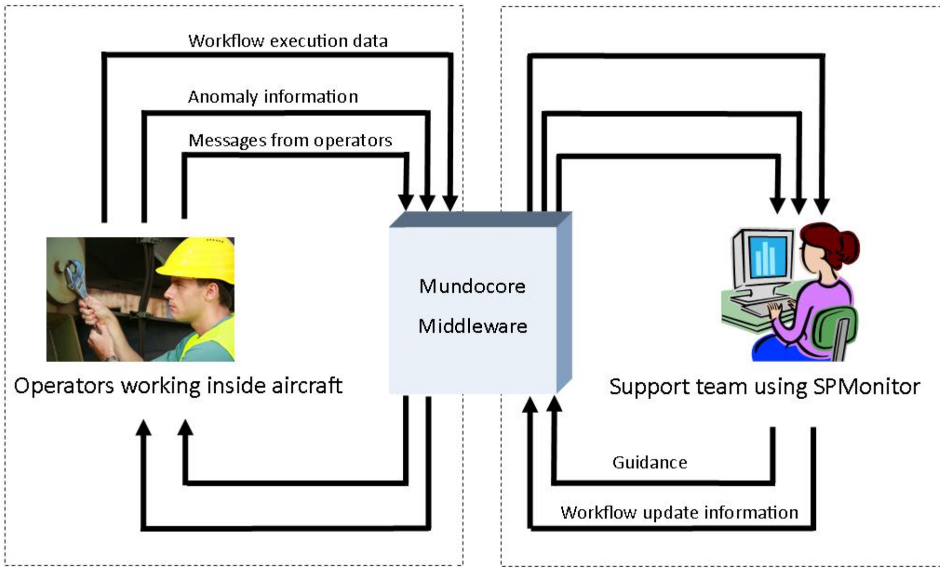

FIGURE 6: Data flows between the operators and the support team

5. EVALUATION

SPMonitor aims at supporting cooperation work by enabling the remote monitoring of workflows proceedings and providing communication mechanisms to exchange information among different actors. The tool also provides interactive means to acquire additional information about workflow activities and react to unexpected events during processes. Due to the purpose of the tool, we think that usability and the perceived usefulness are the most important characteristics to be evaluated. Apart from evaluating the usability of the tool, we were interested in obtaining evaluation results regarding the acceptance of the SPMonitor as new technology in the aircraft assembly processes.

According to the Technology Acceptance Model (TAM) [26], a number of factors influence users’ decisions about how and when they will use new technology. These are ‘perceived usefulness’ defined as "the degree to which a person believes that using a particular system would enhance his or her job performance" and ‘perceived ease-of-use’ defined as "the degree to which a person believes that using a particular system would be free from effort". A six-indicator measurement for the usefulness of technology using the example of email was introduced by Davis. In our evaluation we reused some of these metrics.

For the evaluation we used an empirical usability testing approach, which relied mainly on the coaching method, thinking aloud protocol [27] and post-test questionnaires constructed to mirror the usability measurement discussed above, and secondly a focus group method [28]. The focus group comprised seven researchers with heterogeneous experience in workflow management, semantic knowledge modelling, services and support tools.

The practical implementation of the evaluation followed the aircraft manufacturing scenario, in which the electrical assembly procedure is presented from the planning stage to its certification, including the treatment of an unexpected event during the process. For the empirical usability testing, the researchers, usability specialists and domain experts from EADS were invited to participate. The test was started by clarifying the goals, objectives and intended purpose of use of SPMonitor. Instructions for completing the test tasks were also given on paper so those involved in the test could familiarise themselves with the tasks before starting the test. After the introduction of software, the participants were asked to perform the aircraft manufacturing scenario related tasks with SPMonitor.

First of all, the empirical usability testing gave us confirmation that SPMonitor is considered a useful tool by its end users and that the chosen visualisation techniques are suitable for monitoring workflows. In addition, the provided interaction functionalities were seen as adequate by the test participants. For example, a test participant from EADS estimated that the chat feature is sufficient for resolving 90% of the encountered problems. At the same time, usability testing revealed some ideas on how to improve the tool. For example, the distinction between main workflows and sub-workflows should be clearer in the visualisations. The activities that contain sub-workflows should be represented more explicitly and more general views representing hierarchy levels of different workflows should be provided. Another feature that received some criticism was the anomaly information dialogue. It was suggested that the dialogue should provide more detailed information about the unexpected event. Finally, participants felt that the graphical user interface should indicate more clearly those activities which were being performed in parallel.

In the final phase of the test process, the test participants were asked to fill out a questionnaire, which included questions related to the perceived ease-of-use and usefulness of the tool. The questionnaire contained both questions on a Likert scale from 1-5 and open questions requiring a written answer. Figure 7 presents the average response levels with numerical answers.

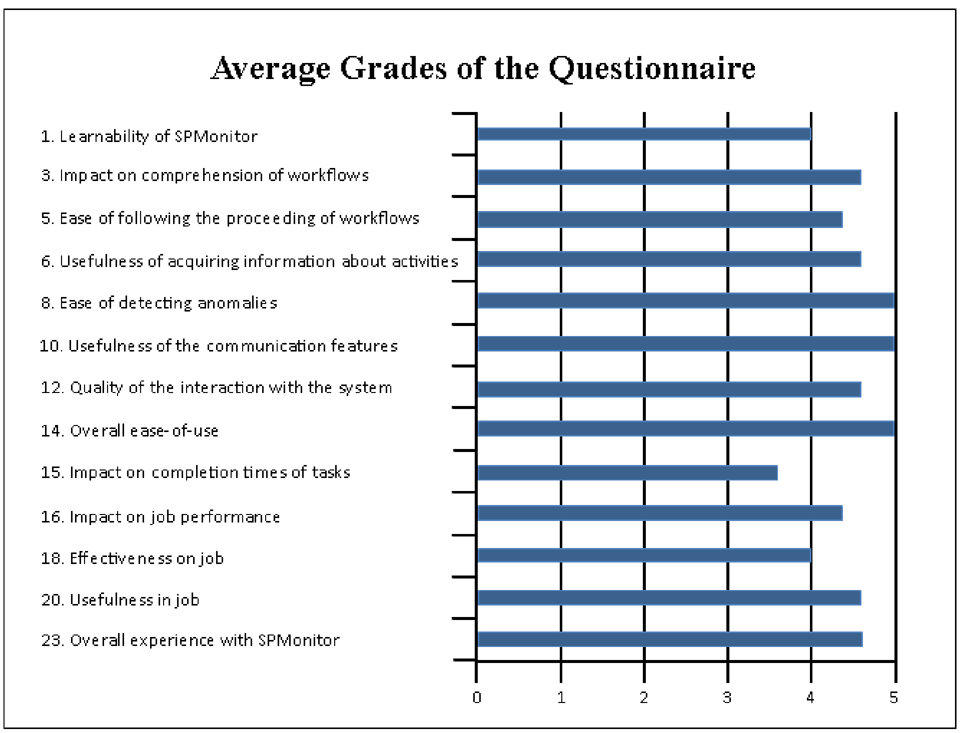

FIGURE 7: The results of the questionnaire

As can be seen the overall response level is quite high. Only statement number 15 has an average grade of below 4. One of the objectives of SPMonitor is to provide time savings in aircraft manufacturing processes, especially by enhancing anomaly management procedures. Apparently, some of the test participants were not convinced that they could save a substantial amount of time in dealing with unexpected events by using SPMonitor. On the other hand, it may have been difficult for test participants to provide any accurate estimates of how much time the system would save them, as some of them were not the intended end users of the approach they evaluated. The written responses also reflected the positive reception of SPMonitor, as they included many encouraging comments. For example, one participant stated that “It’s an interesting tool to present to EADS business units”. These kind of comments increase the motivation to further develop the tool.

The feedback obtained from the focus group session gave us many fresh ideas for future research work and the development of SPMonitor. For example, many of the focus group members suggested that SPMonitor could be useful in the domain of project management. A concrete use case example is monitoring the progress of a software development project in order to see the current state of different tasks and examining potential problems that may come up. Potential was also seen in using the tool in project planning, where SPMonitor could enhance such tasks as project configuration and resource assignment. Finally, the focus group suggested numerous other domains in which SPMonitor could be useful. These domains include education, real estate maintenance and health care.

Many of the focus group session participants also considered that SPMonitor could use the capabilities provided by semantic technologies more effectively. Currently, SPMonitor stores data related to past workflows, which enables the performance of sophisticated analysis and diagnostics reports. Thus it supports the design phase of workflows, by enabling to better estimate how long the execution of workflows with certain types of activities, transitions and resources (e.g. tools and operators) will take and what kind of anomalies can be expected. However, if the tool were to use the powerful reasoning capabilities provided by semantic technologies more efficiently, it could dynamically produce more sophisticated analysis containing information describing issues such as data dependencies of a workflow in run-time. Additionally, the more efficient utilisation of semantic technologies could improve the SPMonitor’s ability to deal with unexpected events.

Although, the evaluation carried out in this study gave some insight into the potential of the tool, it must be borne in mind that the actual verification of the approach can only be done in a real production environment where the way in which the approach copes with the demanding requirements of final aeronautical assembly lines can be tested. The feedback provided by end users is also likely to provide a more accurate picture of the usefulness of the tool, as they have more experiences from using the approach. Moreover, the testing in a real production environment will facilitate the gathering of quantitative data, which will provide more accurate information on how much time SPMonitor actually saves, or whether it has an impact on the occurrence rate of anomalies, for example.

6. CONCLUSIONS AND FUTURE WORK

Digital means and computer-supported collaboration techniques are being used widely in engineering in many production domains. It is adopted in particular in the modelling and simulation of the manufacturing processes in large industrial companies. However, the monitoring and visual support to facilitate the coordination functions of run-time productive environments is still a challenge.

In this paper, we have proposed semantically empowered visualisation aids to support collaborative processes and corrective decision-making for various actors, such as operators, support teams and station managers involved in the execution of the productive process. The resulting approach dynamically visualises information related to workflows, including the processes, participants and other resources involved. An important aspect is also to show illustratively the possible anomalies that may occur during a workflow and allow users to react more efficiently to the problems. The ability to provide a “global view” of workflows improves the overall comprehension of processes and allows users to gain a better overall picture of the whole ecosystem.

The approach also specifies a new workflow ontology that defines concepts, relationships and attributes needed for describing workflows and other related information. The semantic modelling and processing of workflows has many benefits as it enables more sophisticated diagnosis and analysis possibilities, and also facilitates more efficient run-time decision-making capabilities. Moreover, the use of semantic technologies enhances the integration of heterogeneous workflow-related information into a single data model. However, the utilisation of semantic technologies also presents a challenge and therefore further research must be carried out on how to better exploit the full potential they offer. Additionally, more information regarding what kind of diagnostics and analysis information would be most useful for end users should be acquired from domain experts.

The approach has been validated within the actual application and use cases associated with final aeronautical assembly lines. The evaluation was carried out in two phases: firstly a focus group session was organised and secondly, analytical user tests were performed. The focus group session provided numerous suggestions on possible directions in which the tool could be developed. The analytical user tests provided information on the system’s ability to meet its requirements in terms of usability and perceived usefulness. Through the light evaluation performed in this stage, SPMonitor has demonstrated its potential in terms of the improvement of productivity, flexibility and product quality. However, a thorough verification of the tool would require more extensive testing in a final production environment.

Apart from the aeronautical domain, we believe the tool can also bring about benefits to other application domains such as logistics, education, real estate maintenance and health care, thanks to the extensible capabilities of the tool in terms of domain-specific ontologies and additional visual graphics libraries.

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PUBLICATION V

Towards Semantic Facility Data Management

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Towards Semantic Facility Data Management

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***Abstract*—Nowadays, facility management is realized with different information systems, which provide a comprehensive view for the management. Building Information Modelling (BIM) encompasses a computer model of a facility, which is utilized throughout the life-cycle of the building. To enable a more holistic view on facilities' conditions (e.g., energy efficiency, indoor environment, maintenance and repair) we present an approach which enhances the BIM model with semantic indoor measurement data. The enhanced semantic information provides more contextual information about the building; history of conditions, current conditions, and even predictions about the future conditions. In addition, the system ties facility users into the process of facility management by allowing them to view the current indoor conditions and give feedback about the conditions of the building. The resulting semantic facility data management approach was tested in an experiment in which the system was applied in a school building environment.**

Keywords—facility management, semantic technologies, BIM, user-awareness, indoor conditions, sensor measusrements

I. INTRODUCTION

The field of facility management refers to the coordination and maintenance of physical spaces and infrastructures such as office buildings, schools, hotels and government institutions. Efficient facility management requires understanding and engaging different stakeholders including building users, owners and operators. Additionally, although good facility management is traditionally measured by a reduced operating cost, more attention has been given to the impact of the overall qualitative aspects of the work environment on users' perceived satisfaction and ability to work [1].

The requirements of facility management have increased tremendously during the recent years. Especially the growing role of computerized support systems has led to more complicated facility management operations. For example, Building Information Modelling (BIM) has attained widespread attention [2]. BIM represents the process of development and use of a computer generated model to simulate the planning, design, construction and operation of a facility [3]. BIM models are computer generated data-rich and object-oriented representations of facilities from which views and data appropriate to various users' needs can be extracted and analysed to generate information that can be used to make decisions [4]. For facility management's perspective, the BIM models are useful especially for renovations, space planning and maintenance operations [3].

The recent technological advances in pervasive computing and wireless sensors have enabled also new types of facility services. The examples of applications are span from security and surveillance to monitoring of consumption of facility resources (e.g., measuring, logging and comparing water and electricity consumptions). Novel types of building performance measurement methods such as sensor network systems allow extensive heterogeneous information generated within facilities providing valuable information about the current state of a building. While extensive sensor data is collected from different environments there are still significant challenges in converting such data into useful information needed by different facility stakeholders [5].

The utilization of semantic technologies facilitates the management and interpretation of data collected from facilities. For example, the use of resource describing metadata enables more intelligent machine-to-machine interactions, such as reasoning, deduction and semantic searches [6][21]. Moreover, the abilities to merge heterogeneous data and derive high-level context information from low-level measurement data expand the scope of use of semantic technologies in the domain of facility management. While the quantity of data represented with semantic techniques has increased enormously, powerful database techniques for storing, managing and querying semantic data have been developed both by research community and industry [7][8][9].

Although there have been several approaches to utilize semantic technologies in the field of facility management [10][11][12], the potential of semantics is still yet to be fully realized. For example, the benefits deriving from the integration of static BIM data to dynamic facility monitoring data are not extensively exploited or understood. Additionally, more information about field tests and experiments in which these emerging technologies are applied in practical real-world settings taking into account the users' satisfaction perspective is sorely needed.

In this paper, a novel approach for semantic facility data management is introduced. The approach integrates and interprets facility information collected from heterogeneous sources and represents it for different stakeholders, including facility users, maintenance workers and owners. Furthermore, the approach allows facility users to give feedback about the conditions of a building.

The semantic data management approach was tested in an experiment in which it was applied in the Tervaväylä School. Tervaväylä is a state-funded special school and centre for

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development in special needs education and it is located in Oulu, Finland.

Besides the semantic data management approach, the test environment included a building automation system and a wireless sensor network that provided sensor-based measurement data, a server machine that hosted a semantic database and a tablet computer that held a Graphical User Interface (GUI) that allowed the users to examine the visualized facility information and interact with the approach.

The results of the experiment show that with the semantic facility data management approach it is possible to effectively merge and interpret heterogeneous facility data and produce interactive visualizations for different stakeholders. Furthermore, field tests conducted as a part of the experiment indicate that the possibility of examining sensor-based condition (temperature, energy consumption, etc.) information is perceived as a useful feature by the facility users. Moreover, the user interface that allows users to navigate through the school building and give feedback on the conditions of different rooms were found to increase user satisfaction. Additionally, the facility maintenance workers perceived the system as a valuable information resource that offers potential to support their daily activities, work processes and interaction towards the facility users. The suggestions for improvements that were derived from the experiment include fine-tuning the GUI and the visualizations provided by the approach.

The rest of paper is organized as follows. Section II gives a description of the test environment. In Section III the results of the field tests are discussed in more detail. Section IV concludes the paper.

II. TEST ENVIRONMENT

In Fig. 1, the different components of the test environment are presented.

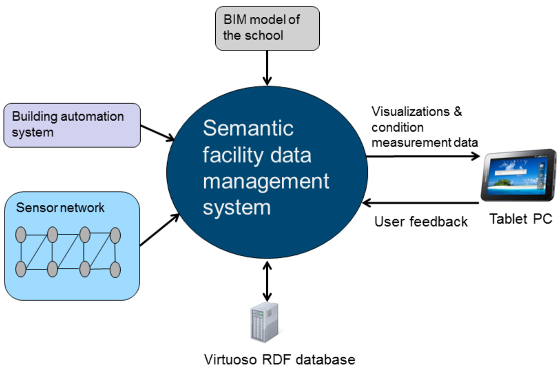

Fig. 1. The test environment used in the experiment

A. *Building automation system*

The building automation system in Tervaväylä School was accessed via RAUInfo [13], which is a service designed for the owners and maintenance workers of properties and which provides continuous monitoring data accessible via web-service interface. RAUInfo offers comprehensive monitoring data on, for example, heating, cooling and water and energy consumption of Tervaväylä School.

B. *Wireless sensor network*

The facility data acquired from the building automation system is augmented with additional measurement data provided by sensors mounted to selected rooms in Tervaväylä School. The sensors were installed to spaces that were uncovered by the building automation system but are actively used by the facility users. The additional sensors provide the following measurement values: temperature, illuminance, carbon dioxide level, moisture, and humidity.

C. *BIM model of the school*

The BIM model of the Tervaväylä School contains information about physical and functional characteristics of the facility. The BIM model represents the design of the building including spaces, objects and other building components. The integration of the BIM model into the overall system architecture provides several benefits. For example, by using the BIM model the different data providing sensors can be located and discovered more easily.

D. *Virtuoso RDF database*

The semantically described facility data is stored to Virtuoso [9], which is a database management system for RDF [14] data. Virtuoso offers numerous data access and storage mechanisms and interfaces. Virtuoso has been widely used platform and is continually developed further and is thus mature enough solution as the RDF database for the facility data. In addition, Virtuoso supports the storage and querying of very large datasets, which is essential in this context, since building automation and additional sensors can provide a large amount of information.

E. *Semantic facility data management approach*

The architecture of the semantic facility data management approach contains three main layers: a data collection and storing layer, a data processing layer, and a data representation layer. The data collection and storing layer is responsible for acquiring, semantically annotating and finally storing the facility-related data into the semantic database. The data processing layer enables interpreting semantically described facility data into more meaningful context information. For example, it realizes SPARQL [15] querying functionalities, manages different user profiles and provides necessary information for visualization views. The semantic data processing capabilities provided by the data collection and storing layer as well as the data processing layer are enhanced by the extensive utilization of ontologies.

Ontologies are commonly used to formally represent a set of concepts within a domain and the relationships between pairs of concepts. Ontologies support modelling a domain and performing reasoning about different entities. Ontologies also specify a shared vocabulary and taxonomy which represent a domain including its concepts and their properties and relations [17]. In semantic facility data management approach, ontologies are utilized for formally representing domain specific concepts and their relationships, and metadata that enables the system to better understand, and reason about the structure and purpose of the data. Moreover, ontologies enable the integration of various data sources by resolving semantic heterogeneity between them.

To support the functionality of the framework, three novel ontology definitions were constructed: Building ontology, Sensor ontology and Feedback ontology. The ontologies are described in more detail in the following sub-chapters.

a) Building ontology

To enable the semantic modelling of data contained within BIM models a new ontology was developed. The resulting ontology for semantically storing BIM data is sketched in Fig. 2.

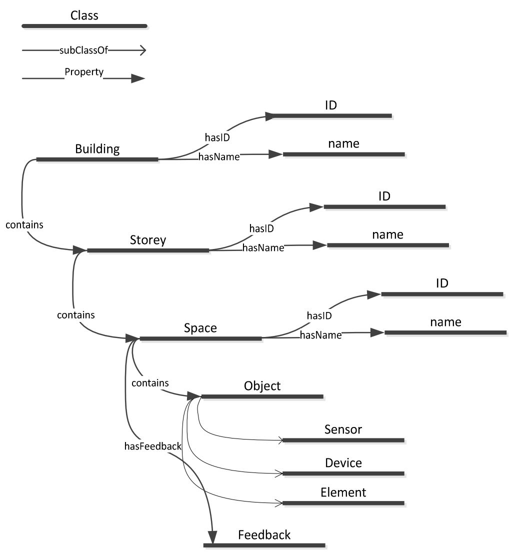

Fig. 2. Building ontology

As presented in Fig. 2, the Building ontology contains four main classes – Storey, Space, Object and Feedback. The next level of the ontology contains subclasses that represent different types of objects, for example, devices. Moreover, each sub class holds its own object type specific properties that provide more specific characteristics about the entities they represent. The Sensor and Feedback classes represent linkages to the other ontologies which are described in more detail later in this section.

Currently, there exist some [18][19][20] approaches that define their own ontologies for semantically describing BIM models. However, for this study it was decided to design a new BIM ontology that adopts some elements from the existing approaches but is especially adapted and optimised for visualisation and monitoring purposes. This more lightweight and flexible ontology is unencumbered by the burden of semantically describing all the concepts and content contained by BIM models. On the other hand, the defined ontology structure offers enough expressiveness for providing comprehensive visualizations and performing sophisticated diagnosis and analysis operations. Additionally, the BIM ontology is general enough to be easily expandable for future needs.

b) Sensor ontology

The system defines a sensor ontology to enable semantic modelling of sensor-based measurement data. Additionally, the sensor ontology facilitates the extraction of high-level context information from various streams of continuous sensor data. In Fig. 3, the designed sensor ontology is presented in more detail.

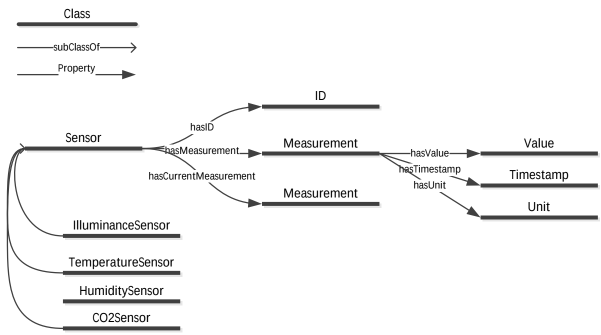

Fig. 3. Sensor ontology

The ontology contains the different types of sensors and their measurements. Every measurement has a timestamp, unit, and value, which are used, e.g., in visualizing the measurements. Each sensor is attached to a specific location in a room in the Building ontology. The location of the sensor can be used in analysing the indoor environment of the target building and to make reasoning about possible events, e.g., heating failure, that would need maintenance

c) Feedback ontology

The feedback provided by facility users is modelled and stored using an ontology description. In Fig. 4 the feedback ontology is presented in more detail.

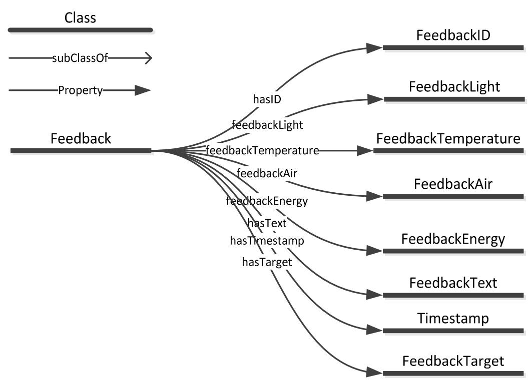

Fig. 4. Feedback ontology

The feedback ontology includes values for the specified feedback attributes: lighting, temperature, air, energy, and free text. The free text field can be used to give plain text feedback about the space. The other fields are numerical values ranging from 0 to 100. For example, in the temperature field a value of 0 corresponds to very cold and a value of 100 corresponds to very hot. The end-user uses a slider with visual cues and a text

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describing the situation. The feedback is tied to a specific location target (e.g., room) in the building. The feedbacks are given a timestamp so that they can be easily compared to the measured indoor conditions from the building automation and additional sensors.

d) Graphical User Interface

The role of the data representation layer is to implement the GUI, which is responsible for creating visualization views and managing interaction between the end-users and the system. The GUI is implemented with HTML5 [16] utilizing graphical libraries optimized for mobile devices. The application is a full web-based application run with a web browser; no native programming language was used. Thus, the application can be used in multiple platforms and devices ranging from computers to tablets and mobile phones. In this experiment, a Samsung Galaxy Tab 10.1 and a laptop were used.

The objective of the GUI is to enhance user awareness by providing means to explore building-related data through visualizations that represent different aspects of the building. Different spaces of the building are represented from an isometric perspective, which provides an overview of the contextual environment and facilitates the discovery of spatial relationships between objects. Moreover, the isometric visualization contains a summary of the measurement information that is provided by the different sensors that are monitoring the conditions of spaces in real-time. The Isometric visualization of a space is shown in Fig. 5.

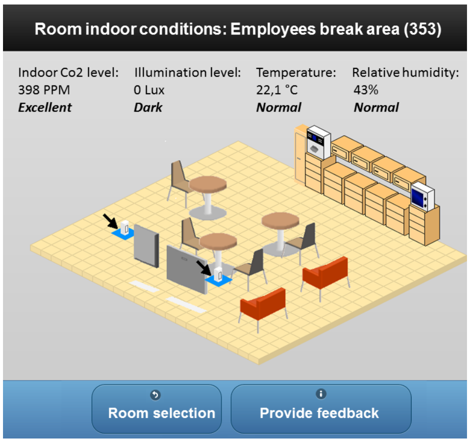

Fig. 5. A visualization of a space

From the isometric visualization the user is able to access a feedback section in which the user can give either general feedback or feedback concerning the existing indoor conditions of a certain space. The approach enables giving either verbal or scaled feedback. Scaled feedback is given by using special sliding clutches in estimating the current status (e.g., from too warm to cold) of four parameters that are temperature, air quality, lighting and energy consumption.

The facility maintenance workers are able to see indoor environment conditions (e.g., temperature, humidity, etc.) of the selected room in line chart visualizations over a selected period of time, e.g., a day or a week (see Fig. 6). Additionally, the facility maintenance workers can view the received feedbacks from the facility users to specific locations in the building.

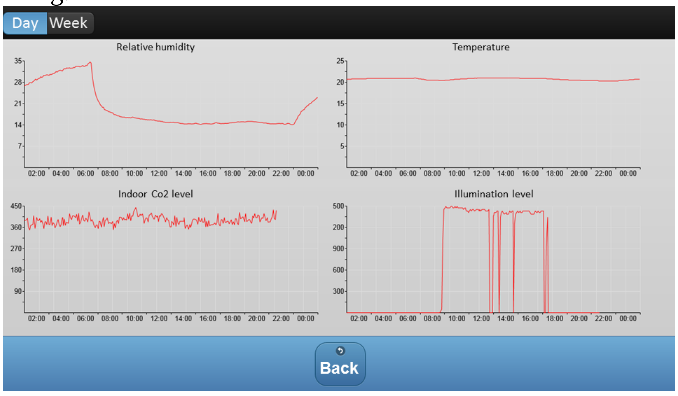

Fig. 6. A historical condition data representation

III. Field Tests

The field tests were conducted in order to achieve the following objectives:

- To validate the functionality of the semantic facility data management approach in real-world settings.
- To examine the usage rate of the semantic facility data management approach among the users.
- To study the effects of the semantic facility data management approach on facility user satisfaction.
- To provide information about how the facility users perceive the existing conditions of the school.

A. Experiment execution

During the field test periods the tablet running the GUI of the system was located in the school employees' break room, where it was available for the personnel to use. The number of people involved in the experiment was approximately 55. In total, three separate test periods were performed and between each period the semantic facility data management approach was improved according to the received user feedback. The times of the test periods are shown below.

Field test 1: 4/12/2012 – 4/1/2013

Field test 2: 1/2/2013 – 15/2/2013

Field test 3: 26/3/2013 – 12/4/2013

B. Experiment results

After the field tests the usage metrics were analysed. Furthermore, an additional questionnaire was prepared in order to measure the perceived ease-of-use and perceived usefulness of the approach. The questionnaire used a five level grading system, where five is the best and one the worst grade, three being the average. Users were able to answer the questionnaire anonymously.

1) Results of usage metrics

The usage metrics indicate that the interest towards the approach was at its peak during the first field test period, in which the different features were used the most frequently. During the second and the third field test periods the users were probably more familiar with the approach and hence used it only when they were interested in the conditions of a certain room or wanted to give feedback about a specific deficiency, for example. A condensed summary of the data obtained from the usage metrics are shown in Table I.

TABLE I. SUMMARIZED USAGE METRICS DATA

	Field test 1	**Field test 2**	**Field test 3**
Main page opened	164	12	11
Info page opened	102	40	21
Feedback sent	18 (of which 7 written)	2 (0)	5 (3)

1) Results of the numerical feedback

According to the numerical feedback received the school employees were mainly satisfied with the indoor environment. However, temperature conditions in different spaces received some negative feedback. When comparing the negative feedback to other facility data managed with the approach it was discovered that the outside weather had an effect on how people perceived the indoor temperature. More precisely, during a cold winter day the indoor temperatures were usually perceived too low whereas a sunny day had an opposite impact. Additionally, when analysing the visualizations of different spaces it was discovered that the negative temperature feedbacks were focused on rooms that contained large windows, which apparently strengthen the effect of warm or cold outside temperatures.

2) Results of the questionnaire

To summarize the questionnaire results, the visualizations offered by the semantic facility data management approach were considered as an important and useful information source by the facility users. However, the usability of the approach was found to require improvements. Moreover, it was perceived as difficult to give written feedback with the tablet. In addition, some data representation techniques used by the visualizations were regarded as difficult to understand. The background knowledge of the end-users on using tablets probably has an effect on the overall satisfaction on the user interface.

The possibility to give feedback anonymously was considered a very positive feature. In more detail, the users felt more convenient to give feedback with a tablet than, e.g., a bigger info screen (if the user wanted to give textual feedback, he/she could do so privately with the tablet). However, according to the questionnaire results a small portion of the employees were not interested in learning to use the tablet PC or the GUI of the approach, which hindered their participation.

3) Feedback from the facility maintenance workers

Besides the field test periods, the approach was introduced to the facility maintenance workers of the Tervaväylä School. The facility maintenance workers were familiarized with the approach and they were given an opportunity to test it. Afterwards, the facility maintenance workers answered a questionnaire that measured the perceived ease-of-use and perceived usefulness.

According to the questionnaire results, the tablet was considered as a useful tool and the user interface of the approach was perceived as clear and easy to use. The possibility to receive feedback directly from the users of the building was considered as an interesting feature. However, the facility maintenance workers were a bit concerned whether they have enough resources to react on every comment made through the system. A suggestion made by the facility maintenance workers was to use some kind of filter to extract the most important notices of defects or service requests from the received feedbacks.

In general, the facility maintenance workers appreciated the idea of having a single interface that is used for observing the information of the building. Currently, the information that they need is scattered in three different systems. Also graphical representations of sensor-based measurement data received positive comments. However, according to the facility maintenance workers the approach should offer more flexibility in setting the time range for observing different sensor data measurements. The final conclusion that emerged from the questionnaire was that more advanced means to give additional information through the approach should be provided. For example, it would be useful to inform the facility users about the water or heating system outages or the testing of fire alarms.

IV. CONCLUSIONS AND FUTURE WORK

In this work, a novel approach for facility data management was introduced. The approach utilized semantic technologies to integrate heterogeneous facility data and interactive visualizations to improve user awareness. The approach also offered efficient and easy-to-use mechanisms for providing feedback. Moreover, the approach aimed at aiding the work of facility maintenance workers by offering a unified interface to examine building data and to interact with the facility users.

Results of an experiment, in which the approach was used in real-world settings, were also presented in the paper. The results indicate that by providing real-time information about indoor environment in a meaningful form and by offering convenient ways to give feedback, the customer experience for the facility users can be improved. Furthermore, with the approach the facility maintenance workers are able to better adjust the conditions according to the needs of the users and be aware on users' perceived satisfaction and ability to work. Moreover, semantic techniques were found to be adequate in terms of performance and scalability in real world facility data management activities. Finally, it was discovered that the existing indoor conditions in Tervaväylä School are in a satisfactory level.

The future work includes improving the deficiencies found during the experiment as well as further developing the approach. The possible developing activities include, for example, integrating the approach with existing energy management systems, providing enhanced visualizations that facilitate the visibility of maintenance services to the facility users and utilizing the collected information in the proactive prevention of problems. Furthermore, in order to improve the abilities of the approach to support the tasks of different stakeholders (e.g., maintenance workers, facility owners) a more throughout analysis of their needs and requirements should be conducted.

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Series title and number

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Title	**Semantic visualization for smart spaces – merging the material and digital worlds**
Author(s)	Ilkka Niskanen
Abstract	The trend towards a more sensitive, adaptive, and responsive built environment has led to the concept of smart spaces. A smart space can be viewed as a physical environment in which smart objects collaboratively and continuously monitor the environment, interact with users, and adapt their behaviour according to information gathered from the physical environment and cyberspace. The development and management of smart spaces requires not only considering the entire life-cycle and physical structures of the built environment, but also understanding the collaboration and interdependencies between devices, services, and stakeholders. As a result of this diversity, efficient smart space life-cycle management requires the involvement of multidisciplinary teams of professionals that bring knowledge from their specific fields of expertise. As multidisciplinary teams are increasingly being implemented in the development and management of smart spaces, the actual work is more often globally organized, which promotes geographically dispersed teams. However, the utilization of geographically dispersed, virtual teams often creates a sort of collaboration paradox. While organizations need to have a proper level of diversity to ensure a high level of creativity and innovation, more distance factors affect the overall collaboration performance. The main results of this dissertation are software artefacts that aim to support the development and management of smart spaces. By anchoring illustrative visual representations into formal semantic data representations, the artefacts enable addressing some of the challenges related to multidisciplinary collaboration work. The utilization of appropriate visualization techniques and ontology representations enables different processes related to smart space development and management to become more understandable, which reduces, for example, the knowledge and communication gaps between collaboration stakeholders.
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Nimeke	**Älytilojen semanttinen visualisointi – materiaalisen ja digitaalisen maailman yhdistäminen**
Tekijä(t)	Ilkka Niskanen
Tiivistelmä	Viimeaikainen kehitys, jossa rakennettu ympäristö kykenee yhä tehokkaammin tarkkailemaan ympäristössään tapahtuvia muutoksia ja reagoimaan niihin tarkoituksenmukaisilla tavoilla, on johtanut älytila-käsitteen syntyyn. Älytila voidaan nähdä fyysisenä tilana, jossa älykkäät esineet havainnoivat ympäristöä yhteistyössä toisten objektien kanssa adaptoiden jatkuvasti toimintaansa ympäristöstä kerätyn tiedon mukaisesti ja ollen vuorovaikutuksessa tilan käyttäjien kanssa. Älytilojen kokonaisvaltainen kehitys ja hallinta edellyttävät paitsi rakennuksen elinkaaren ja fyysisten rakenteiden huomioimista myös laitteiden, palveluiden ja sidosryhmien välisen yhteistyön ja riippuvuussuhteiden ymmärtämistä. Älytilojen monimuotoisen toimintaympäristön johdosta niiden elinkaaren tehokas hallinta vaatii monialaisen asiantuntijaryhmän mukanaoloa. Asiantuntijaryhmässä kukin jäsen tuo prosessiin oman spesifisen alan asiantuntemuksensa. Samanaikaisesti kun monialaisia ryhmiä käytetään yhä enenevissä määrin älytilojen kehityksessä ja hallinnassa, itse työ on usein globaalisti organisoitua. Tämä lisää tarvetta hyödyntää työryhmiä, jotka ovat myös maantieteellisesti hajautettuja. Maantieteellisesti hajautettujen työryhmien hyödyntäminen luo kuitenkin usein niin sanotun yhteistyön paradoksin: vaikka organisaatiot tarvitsevat tietyn määrän erilaisuutta ja monialaisuutta turvatakseen korkean luovuuden ja innovointikyvyn tason, vaikuttavat erilaisuustekijät toisaalta negatiivisesti yhteistyön kokonaisuustehokkuuteen. Tämä väitöskirjatyön päätulokset ovat ohjelmistoartefakteja, joiden tavoitteena on tukea älytilojen kehitystä ja hallintaa. Yhdistämällä havainnolliset visuaaliset esitykset formaaleihin semanttisiin malleihin artefaktit auttavat vastaamaan osaan monialaiseen ja maantieteellisesti hajautuneeseen yhteistyöhön liittyvistä haasteista älykkäiden tilojen kehityksessä ja hallinnassa. Soveltuvien visualisointitekniikoiden ja ontologiaesitysten hyödyntämisen avulla eri älytilan kehitykseen ja hallintaan liittyvät prosessit voidaan tehdä ymmärrettävämmäksi ja näin pienentää yhteistyösidosryhmien välillä olevia tietämyseroja sekä edesauttaa kommunikointia.
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VTT SCIENCE 95

Semantic visualization for smart spaces – merging the...

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