Ontology-driven development of web services to support district energy applications

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Abstract

Current urban and district energy management systems lack a common semantic referential for effectively interrelating intelligent sensing, data models and energy models with visualization, analysis and decision support tools. This paper describes the structure, as well as the rationale that led to this structure, of an ontology that captures the real-world concepts of a district energy system, such as a district heating and cooling system. This ontology (called ee-district ontology) is intended to support knowledge provision that can play the role of an intermediate layer between high-level energy management software applications and local monitoring and control software components. In order to achieve that goal, the authors propose to encapsulate queries to the ontology in a scalable web service, which will facilitate the development of interfaces for third-party applications. Considering the size of the ee-district ontology once populated with data from a specific district case study, this could prove to be a repetitive and time-consuming task for the software developer. This paper therefore assesses the feasibility of ontology-driven automation of web service development that is to be a core element in the deployment of heterogeneous district-wide energy management software.

Keywords: ontology design, domain engineering, software development, intelligent web services, semantic web

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1. Introduction

Heterogeneity of data representation models and communication protocols is one of the numerous challenges faced by novel urban energy systems, such as microgrids and district heating and cooling networks [1][2][3][4]. The holistic and ICT (Information and communications technology) driven management of these energy systems alongside other social, technical, economic and political systems is critical for the sustainable development of cities through the smart city paradigm [5][6][7][8]. Further, the optimal coordination of the distributed energy resources is a complex problem that requires intelligent software control [4][9][5]. The components of such intelligent software energy management frameworks need to be able to retrieve dynamic local data from a wide range of devices and systems, including sensors, smart meters, actuators, BMS (building management systems), EMS (energy managements systems), that do not necessarily share common data models or communication protocols, as is the case in the context of an urban district. This paper addresses this gap through an ontology-based software to support the semantic integration of local energy management systems with district-wide intelligent coordination software. The application of ontologies as a common vocabulary among agents will be presented within the context of European project RESILIENT. This project aims to couple renewable energy sources and energy storage within low carbon urban environments [10], through the application of a novel ICT framework. Specifically, RESILIENT couples real-time sensor data and weather forecasts with a simulation engine and a semi-automated optimization engine to provide decision support to all energy management stakeholders from both an environmental and a market-driven perspective. Further, RESILIENT aims to answer the following overarching question: can these heterogeneous physical and virtual components be effectively integrated through a District Information Model (DIM); a semantically formalised description of the socio-technical state of the network? In order to support the objectives of the RESILIENT ICT framework, the final product of this research will play the role of a mediator, i.e.

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an intermediate layer between the clients (the software frameworks that automate decision-making on the district energy system) and the local servers (the BMS/EMS that control and monitor the various components of the district energy system) [11]. A common vocabulary is required to overcome the diversity of
35 metadata in both the intelligent energy management frameworks and the local BMS and EMS. A domain specific ontology is used to capture the underlying real-world concepts that are represented by these metadata (the domain here is district scale energy management) [12]. The development process of the mediation component depends on the machine-interpretable knowledge expressed
40 by this domain ontology. Such an ontology, once deployed in the right operational environment, can support real time knowledge querying by the underlying multi-agent framework [13]. The research presented in this paper produced a two-fold solution to the issue of deploying district-wide energy management software. Firstly, in order to provide a semantically accurate representation of the
45 district physical components and stakeholders, a socio-technical ontology of district energy, named ee-district has been developed. The name ee-district stands for energy efficient district, as its final application is intended to be the optimal coordination of the district energy resources. Secondly, a preliminary way of consuming the ee-district ontology has been implemented. The development
50 of a semi-automated web service generator should facilitate the integration in district-scale energy systems of:

- software components intended to monitor or control energy resources and infrastructures in the district (whether they are accessible directly or through a BMS);

55 - and software components intended to map the presented data model of these resources and infrastructures with the ee-district semantic model.

The objective of this research is to assess the feasibility of ontology-driven automation of web service development that is to be a core element in the deployment of heterogeneous district-wide energy management software. Following
60 this introduction, Section 2 establishes the grounds for the development of the

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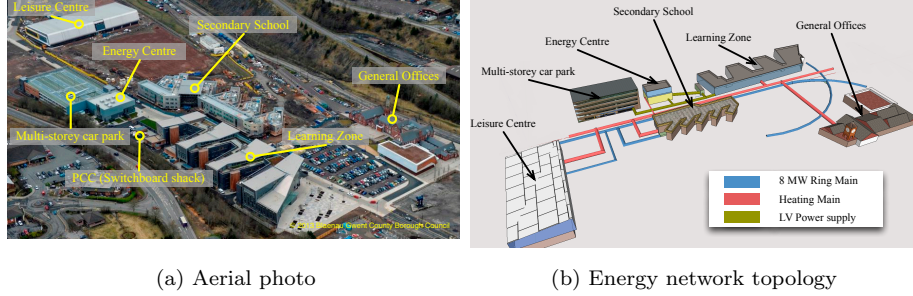(a) Aerial photo   (b) Energy network topology

Figure 1: The Works, study district in Ebbw Vale, UK.

ee-district ontology by means of a real-world use case. Then, Section 3 gives a short literature review in the related fields of semantic modelling applied to energy applications, ontology engineering methodologies and metaprogramming. In light of this theoretical background, Section 4 presents the methodology followed by the authors to develop the ontology and the web service generator. Section 4.3 details the architecture of the ee-district ontology. Sections 5 and 6 discuss the effectiveness of the designs presented in the previous section by means of their implementations. Section 7 discusses notable related works and the potential benefits of the ontology-driven generation of web services to the field of urban energy management before the conclusion gives an overview of the work achieved as well as directions for future work.

2. Motivating use case

The RESILIENT project should cater to a wide range of socio-technical energy management problems faced by facility managers or owners. These problems are getting more complex due to the increasing amount of factors that needs to be taken into account, to deliver a holistic (i.e. systems engineering) solution. One such case study was identified in the Ebbw Vale pilot site. The district information model aims to cater to such problems. The Ebbw Vale pilot site, a district named The Works, is situated in South Wales, United Kingdom covering a total area of 750,000 m2. It has newly constructed, as well as

retrofitted, buildings, operating in various sectors educational, commercial and leisure. As shown in Figure 1, the site consists of a learning centre, schools, offices, a multi-storey car park, a leisure centre and an energy centre. The energy centre is the source of heating to buildings and also provides low voltage electricity directly to the learning centre and the car park. The energy centre consists of a 342 kW gas-fueled CHP (Combined Heat and Power), a 1.6MW biomass boiler, and additional supplementary gas boilers. It is also the main source of heating energy for the buildings on site. The CHP produces electricity, which is used mainly by the learning centre. Electricity is also being supplied by an 8 MW HV ring main supply. One of the use cases identified in this pilot site involves optimising the multi-energy generation mix of the energy centre. Currently the heat exchangers of the energy hub, which provide district heating, work at fixed setpoints. Optimisation of setpoints according to varying demand and environmental conditions could bring about significant energy savings and greenhouse gas emission reduction. The ee-district ontology help capture semantic knowledge in a district, like Ebbw Vale, and makes this information machine understandable. The information collected consequently helps decision making software to optimise the day to day operations in the district. The optimization aims to reduce green house gas emissions whilst taking into account the various constraints — technical, environmental, economical. The proposed ee-district ontology will play a key role in supporting the delivery of semantic optimization and decision making capabilities as elaborated in the paper.

3. Theoretical Background

This section summarizes the relevant literature with a focus on: ontologies for energy management, ontology engineering methodologies, and metaprogramming and web services.

3.1. Ontologies for energy applications

Semantic modelling in energy applications has the potential to support (a) automatic control of the grid operation, (b) computer-aided decision making for

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human intervention, (c) data sharing among numerous components and tools, and (d) integration of the grid functionality [14]. Rohjans et al. (2010) combined domain ontologies based on the Common Information Model (CIM) with Object Linking and Embedding for Process Control Unified Architecture (OPC UA) and web services in order to design service oriented architectures for smart grid utilities [15]. In short, the proposed semantic model allowed to identify which service provides which function under which conditions. Conversely, Uslar et al. (2010) pointed out limitations in the CIM, in terms of (a) scalability (integration of new objects and relations corresponding to new grid technologies), (b) multi-utility support, and (c) integration of the IEC 61850 standard for the design of electrical substation automation (information technology layer and control layer) [15]. Zhou et al. (2012) developed a smart grid information model relying on ontologies for: electrical equipments, organisations, and infrastructures; factoring in weather and spatio-temporal information. Andrn et al. (2013) addressed the problem of adaptability in smart grids [16]. These authors proposed a holistic approach that harmonises modelling, design and validation. Their approach relies on semantic models that extend existing standards. The lack of a self-contained ontology dedicated to district energy management lead the authors to develop their own ontology, which captures the knowledge of this specific domain while relying on a selection of fundamental re-used ontologies.

3.2. Ontology engineering methodologies

Many ontology development methodologies have been brought since the dawn of formal ontology languages, including: Ushold and Kings methodology [17][18][19], METHONTOLOGY [20], On-to-knowledge methodology [21], NeOn [22], and UPON [23]. In the middle of the nineties, Ushold, King and Grninger have popularised some of the now commonly used terminology in the field of ontology development, starting from Tom Gruber's definition of ontology as the specification of a conceptualisation [24], which is now widely accepted in the Artificial Intelligence community and more generally in the field of computer and information science. Their methodology brings together formal and

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informal ontology design approaches. It first helps to categorise ontology usages according to the required level of formality, the targeted purpose and the reusability potential in various contexts. Then it provides guidelines on how to conceptualise a domain of study by collating the involved elements of the considered real world system and by identifying the requirements through usage scenarios and competency questions. METHONTOLOGY also provides guidelines on the main subtasks to develop new ontologies. METHONTOLOGY distinguishes between the actual phases of ontology engineering (planification, specification, formalisation, integration, implementation and maintenance) and the accompanying activities that happen through the ontology life cycle (knowledge acquisition, documentation, evaluation). METHONTOLOGY takes into account the evolutive nature of the ontology throughout its life cycle. On-to-knowledge methodology (OTKM) focuses on the integration of ontology based applications into enterprises to offer systematic knowledge management capabilities. OTKM decomposes the Knowledge Meta Process that frames the ontology development from the feasibility study to the application and maintenance of enterprise ontologies. The practical case study described by Sure et al. in [21] highlights some human issues that appear to be central to the collaborative construction of ontologies: involvement of domain experts along with ontology designers, necessity of live interaction between them, and necessity of computer-aided design tools. The NeOn Methodology for Building Contextualized Ontology Networks intends to improve on the previous methodologies. The methodology defines an ontology network as opposed to standalone ontologies and simply interconnected ontologies by the existence of meta-relationships between the considered ontologies. Nine different scenarios for ontology network engineering are defined, depending on the nature of the reused resources and the way they are reused. Detailed guidelines and templates are provided by the NeOn methodology for ontology specification, non-ontological resource reuse and reengineering, ontological resource reuse and ontology design pattern reuse, thus covering all of the nine scenarios [22]. The Unified Process for ONtology (UPON) takes a software engineering approach based on the Unified

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Process (UP) and the UML. It aims at improving the efficiency of ontology engineering as well as the quality of the resulting ontology products by systematically specifying the interactions between ontology engineers and domain experts. UPON maps the UP workflows (requirements, analysis, design, implementation, test) with the corresponding ontology development phases, consequently making them iterative and incremental by nature. The methodology also specifies, for each phase, the nature of the inputs and outputs, the activities to be carried out and the relative involvements of ontology designers and domain experts. According to the authors [23], UPONs main property, that is inherited from UP, is its flexibility in terms of scale, domain, complexity of the ontology to be designed. The authors applied a methodology that borrows from NeOn and UPON, for more modularity and flexibility.

3.3. Metaprogramming and web services

The main benefit of the research presented in this paper is to present the knowledge expressed in the ee-district ontology in a way that is immediately exploitable by the developers of high-level software components involved in district energy management (such as coordination optimisers, simulation platforms or knowledge visualisers). Web service development environments bring such flexibility and simplicity. Writing the source code that queries the ontology on the one hand and processes the knowledge requests of external components on the other is a highly repetitive and conceptually redundant task that can be handled by automatic code generation [25]. Metaprogramming is the discipline dealing with the automatic construction of programs. Some metaprogramming principles are already widely known by web developers. For instance, server-side software written with PHP language usually generate source codes in Javascript language, embedded in HTML pages that are then interpreted on the client side by the users web browser. Although not directly referring to metaprogramming, this papers approach relates to the work described in Dhraief et al. on their Open Learning Repository [26]. Van Dam and Luzko (2006) defined a generic method to automatically generate Java objects complying with a multi-agent

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system library starting from the instances of an ontology [27], later van Dam et al. (2008) applied the methodology to the agent-based control of distributed electricity generation units [28]. Chlipala (2010) has presented a framework to facilitate metaprogramming in Web applications. One notable use case for that framework is object-relational mapping, i.e. generating the commands that manipulate database records by associating the object-oriented representation in the native language of the web service implementation with the relational representation of records in the databases own query language. tuikys et al. (2009) created a methodology to design web portal generators. The generators themselves are expressed in a certain meta-language, whereas the web applications are implemented using several languages [29]. These authors devise a coherent structure encompassing semantic model for change, program generator model, Web component instance model, and given metalanguages. Their approach of higher-level generators allows a tangible gain in productivity provided that a thorough domain analysis has been conducted initially. Their design process relies on a semantic model resulted from this domain analysis. Lwe and Noga (2002) applied the RECODER[30] metaprogramming environment to the generation of Java-based web services from the viewpoint of remote method invocation [31]. In the light of the design and implementation experience reported in that paper, it is concluded that metaprogramming is well adapted to the generation of web services.

4. Methodology for the design of the ee-district ontology

The Semantic Web technologies and standards, in particular the OWL2 Web Ontology Language [32] and the querying language and protocol SPARQL [33], are well suited to form the foundation of district energy system knowledge representation and manipulation. The key benefits of semantic web technologies, which have been highlighted in the Semantic Web Case Studies gathered by the W3C [34] include: (1) support the interoperability between heterogeneous information systems, (2) separate the information semantics from the underly-

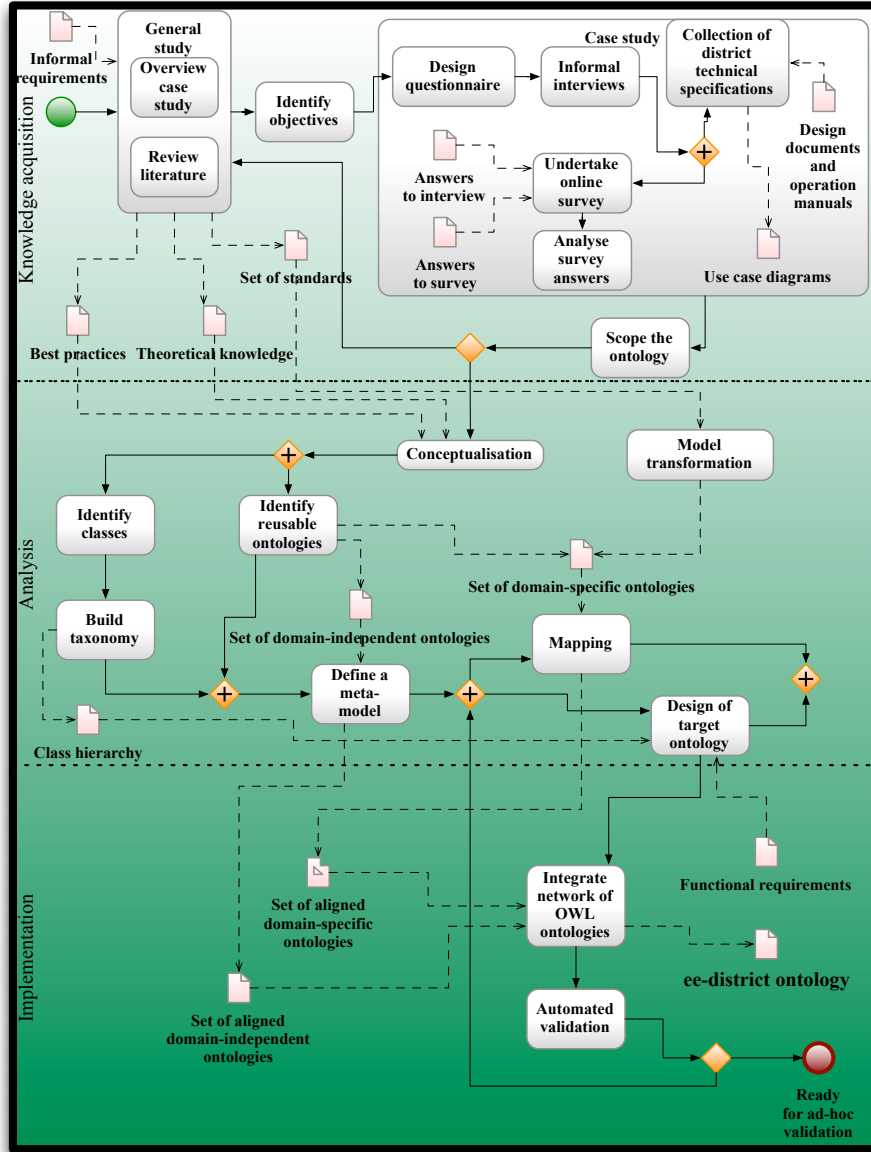Figure 2: *ee-district* development methodology BPMN process diagram.

ing data, (3) help sharing knowledge, (4) formalise knowledge otherwise hidden/implicit in code or database schemas, (5) simplify collaboration for knowledge modeling, (6) reduce modelling effort by allowing the reuse of established

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ontologies, and (7) contribute to the evolutivity and the flexibility of knowledge/data models. Use cases 1 and 7 are particularly of interest to this paper,

with respect to the goal of capturing the underlying real-world concepts of a district energy system to federate the diverse metadata representations in the district ICT-enabled components (e.g. EMS/BMS, intelligent management software ...).

An OWL ontology for energy efficient districts was created and continuously developed according to the knowledge collected throughout the different stages of the methodology. It is informed by the literature, such as [35], and involves a thorough consultation through interviews with stakeholders and questionnaires for facility managers, domain expert knowledge elicitation, various domain standards such as the Common Information Model (CIM) series [36], and existing ontologies. It is an iterative and participative process, given the complexity of the project and the collaborative nature of the work between partners. It can also be noted that, considering the small amount of written or digital artefacts documenting the processes involved in the case study district energy management, the authors did not use text-mining techniques that build ontologies semi-automatically [37].

Information models provide a representation of concepts and their relationships, constraints and operations to specify data semantics. The RESILIENT information model is referred to as District Information Model of energy efficient applications (ee-DIM) and contains the structured information the ICT framework will rely on, i.e. the ontology for energy efficient district (ee-district). All district elements (e.g. buildings, energy systems, network, and users) are formalised in order to allow information to be later processed by software tools. The formalisation is made using an ontology that defines: the elements; their characteristics; their relationships; and the constraints to which they are subjected. Early-stage domain knowledge acquisition is crucial to understand how the ontology is to be used by a third party software or user in the scope of the project. The district energy ontology developed in this work is designed for district multi-energy coordination involving combinations of storage systems,

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generation units, cogeneration units and energy users, in order to:

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- answer queries from decision-making systems (e.g. optimization algorithms, agent-based software); and,

- ensure interoperability between the district coordination entities and building/energy resource levels (requiring mapping interface software, which are not in the scope of this paper).

₂₇₀ The methodology adopted by the authors, which borrows from the more generic NeOn and UPON methodologies without following them closely, is described in the Business Process Model and Notation (BPMN) [38] process diagram in Figure 2 BPMN has been used as it captures activity and sub-activity, input/output artifacts, major decision points and sequences [39]. The ee-district ₂₇₅ information model (i.e. the ee-district ontology) is conveyed through a software system architecture description in the first place. The methodology has also been widely influenced by the Systems and software engineering Architecture description ISO standard [40][41]. It is roughly divided into three parts: knowledge acquisition, analysis and implementation, which are discussed in the ₂₈₀ following sections.

4.1. Domain knowledge acquisition

This can be considered as stage one of ontology development, which is largely based on both literature review and investigation of the experience of key domain actors. Case studies attempt to understand specifics of the actual working ₂₈₅ of the different pilots in the RESILIENT project. Their purpose is to get an idea of how the district works in real conditions. There can be significant differences in functional descriptions of districts in literature and how it would work in reality; hence the importance of this stage. One key part of this stage of ontology development is the questionnaire, which collects information such as district ₂₉₀ energy scheme/layouts, informal description given by facility owners/managers, operational manuals of different entities of a district, understanding of the different functioning of buildings in the district and their demand and supply

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patterns. The questionnaire is split into different sets of questions, where each set is aimed at the different energy producers and consumers in the pilot site. A set of questions is also dedicated to the general day-to-day operations of the district. The questionnaire was answered through a series of interviews, both in person, over the telephone or using electronic forms, and further developed through site visits. A quota sampling technique was used for sampling where in it was targeted at personnel working in the district from different domains. Inputs to the questionnaire were given by the facility manager, the IT manager, the business development officer and the electrical engineer. Like stage one, the development of the questionnaire was also an iterative process. This was also followed in [4] mainly because it enables delimiting the scope of the research and to a certain extent also helps define the tools needed by stakeholders. Furthermore, use cases/scenarios are identified during this stage, which help to determine the scope of the ontology from the application perspective (end use).

4.2. Analysis of acquired knowledge

The following stage of the methodology followed by the authors aimed to identify the relevant concepts, classify them into a taxonomy and map them with the concepts of abstract, domain-independent, existing ontologies. This stage has involved the use of third-party resources , which were not always expressed as semantic web ontologies, e.g. relevant parts of the ISO/IEC 61790 Common Information Model standard were translated from their original UML definition into an OWL ontology (illustrated by the model transformation box in Figure 4).

The ontology produced by the authors would therefore model all the district entities (energy producers, distributors, consumers, storage facilities); the infrastructure for transfer of load (pipelines, power cables); the load schedules; the demand and supply trends or patterns; the major constraints of the overall system and some individual entities; the objectives that are to be met. Most importantly, the relationships between these entities need to be incorporated into the ontology. Once the objectives are clearly defined, it is important to

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identify the different physical components installed in a district as well as the stakeholders involved. This produces an overview of how the district is currently operated. This first site study helps define the scope of the information model. As shown by the first loop in the BPMN diagram of Figure 4 (intermediate outcome of case studies feeding back into the general study), it is an iterative process and will be carried on throughout the development of the ontology. However, the initial analysis of district ought to identify the different components, which constitute a district and how they are linked together. The work on district energy ontology continued then with basic literature review on these different components of a district. For example, it included looking into physical aspects of a district - energy sources (production) and its classification; consumption points; means of distribution of this energy, etc. The ontology also includes social aspects related to stakeholders. The functions and conditions set in the stakeholder entity would have an effect on the running of districts and would contribute to laying ground rules for energy optimization in the district. Hence, this is a very important part of the district energy ontology, which would look to define some of the boundaries for the various optimization problems to be solved. Some key elements of the District energy ontology that were concluded during this stage are:

- the ontology is to be used to model energy-related information at district level;

- the ontology should support the development of tools, which enable real-time decision making for district energy optimization;

- it is to be developed using the OWL Semantic Web Language, providing the ontology engineers with a good extension of modelling formalisms;

- and the ontology needs to be linked with other standards and accepted ontologies.

The following section describes the structure of the resulting ontology.
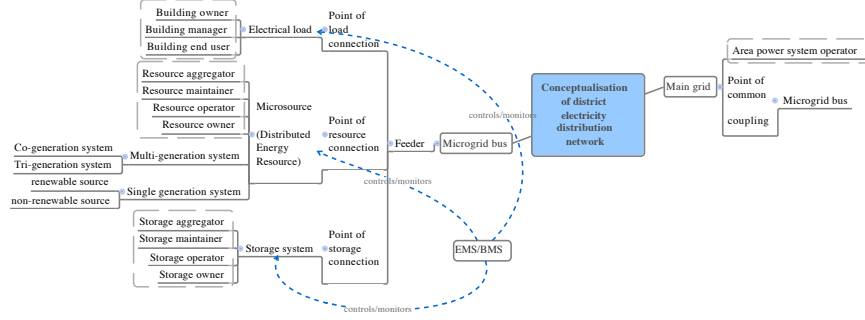
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Figure 3: Conceptualisation of district power networks.

4.3. Implementation architecture of the district energy information model

In the RESILIENT project, a district is defined as a holistically managed and self-encompassing built environment entity composed of a diverse social community, a grouping of buildings, public spaces, roads, undergrounds and utilities, including the energy supply sub-systems, which form the focus of this paper. A district energy system is a system from the *system thinking* viewpoint [42], as it is a set of coherently organised and interconnected components (buildings, facilities and infrastructures as well as a community of stakeholders and end-users) that produces a characteristic set of behaviours in order to achieve the liveability and the sustainability of the district. Considering the level of autonomy exhibited by the different parts of a district, the duality between their own purposes and the district overall purpose, the potential dynamics of their interconnection, their relative independence, and the unforeseen emergence of a global behaviour, a district energy system is also a *system of systems* [43].
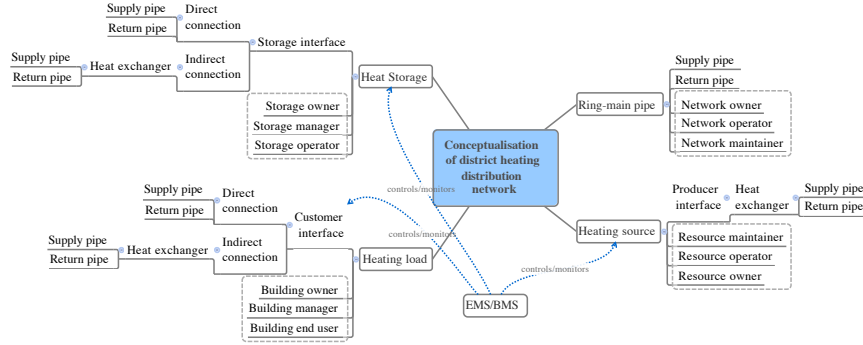
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Figure 4: Conceptualisation of district heating networks.

As well as modelling districts as both a system and a system of systems, it is also useful to consider a district as a socio-technical system when aiming to holistically model its behavior. Van Dam describes a *socio-technical system* as a number of separate yet interacting systems from the both social and physical domains where each is governed by its own laws [44]. By adopting this modelling paradigm it is possible to formalize the effects of cross-contextual interactions within a system. As a district consists not only of the buildings and infrastructures within it but also the people and organisations, it is useful to consider a district as a socio-technical system to understand these complex interactions.

The semantic web environment, introduced in Section 4, can serve as the foundation for the representation of systems. It lacks however the features (such as expressivity for topological/mereological relationships or social vs technical interactions) that have been used to build a model of energy efficient district (the ee-district ontology) that grasps both the conceptualisations depicted in

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Table 1: Informal competency questions, dynamic monitoring.

Dynamic monitoring
What is the electricity demand or electricity load given a *consumer name* and a *timestamp*
What is the heating demand or heating load given a *consumer name* and a *timestamp*
What is the total electricity demand for a given *timestamp*
What is the total heating demand for a given *timestamp*
What is the total generation capacity of heat for a given *timestamp*
What is the total generation capacity of electricity for a given *timestamp*
What is the schedule of production given a *producer name* and *day*
What is the schedule of consumption given a *consumer name* and *day*
What is the rate of production given a *producer name* and *timestamp*
What is the heat load given a *consumer name* and *timestamp*
What is the electricity load given a *producer name* and *timestamp*
What is the energy loss given *physical connection* and *timestamp*
What is the cost of buying electricity/gas from the national grid for a given *timestamp*
What is the cost of producing heat/electricity for a given *component* and *timestamp*
What is the cost of storing energy for a given *component* and *timestamp*

Figure 3 and Figure 4 and the three system theories (system thinking, system

380   of systems and socio-technical systems) mentioned in the previous paragraphs. Competency questions are also a useful way to determine the scope of the ontology where a set of questions are listed; which a knowledge base based on the ontology should be able to answer [19]. Competency questions are sketches; hence the list in Tables 1 and 2 is not exhaustive. The ee-district ontology is

385   built by extracting the abstract concept(s) embedded in the competency questions (that is in the abstract concepts that the authors have identified in district

Table 2: Informal competency questions, static information.

Static topology
Name the producers that supply electricity to the entity given a *consumer name*
Name the producers that supply heat to the entity given a *consumer name*
Name the companies that operate the metering devices that measure the amount of heat consumed by the entity given a *consumer name*
Name the companies that operate the metering devices that measure the amount of electricity consumed by the entity given a *consumer name*
Optimisation
List constraints given a *consumer name*
List preferences/priorities given a *consumer name*
List constraints given a *producer name*
List preferences/priorities given a *producer name*
Topological information
List all the connections given a *producer URI*
List all the connections given a *consumer URI*
List all the physical boundaries given a *physical connection URI*
List the maximum capacity of given a *physical connection URI*

energy systems) in order to answer them (and to implement the corresponding SPARQL queries later on). This can be achieved by reusing relevant parts of existing ontologies, each of them fulfilling a specific abstraction or domain-related need, thus leading to a modular approach [45]. All these ontology modules, along with the target ontology, constitute the ontological definition of the ee-district model. The authors have identified groups of ontology modules that are essential to the abstract infrastructure of the ee-district ontology and its application domain expressiveness. For implementation simplicity, in particular to prevent additional alignment effort, most of these ontological modules are reused from the ontology for Computer Aided Process Engineering (Onto-CAPE) [46], developed at RWTH Aachen University. In theory, any module

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could be replaced by another conceptually equivalent implementation, however, in practice, due to the conceptual gaps between different upper level ontologies, such replacement could greatly affect the structure of ee-district. Other examples of well established sets of upper layer ontologies are the IEEE Suggested Upper Merged Ontology (SUMO [47]) and the Wikipedia-based DBPedia [48] ontology. The main modules that constitute the semantic substructure of the ee-district ontology are:

- mereology: the mereology module defines part-whole relationships of two types, aggregation and composition.

- topology: the topology module defines connectedness models, node and edge concepts.

- system: the system module provides conceptualisations of systems, kinds of systems and taxonomical semantics for hierarchical systems of systems.

- time: emergent properties of systems are path-dependent [49], the sequence of past decisions influences the current behaviour. The time module defines a specific coordinate system for time-dependent data that goes beyond the built-in XML time constructs.

- physical dimension: the physical dimension module allows the representation of physical quantities, dimensions and units, that are required to describe physical and economic properties of the district energy system components.

- socio-technical system: it allows the representation of real or abstract networks both at a technical level (involving physical elements) and social aspects (involving decision making entities).

- domain ontologies: all the modules above are domain independent, but the district energy ontology also relies on domain specific ontologies. Some reused ontology modules are derived from standardised information models.

Some of the ISO/IEC 61970 standards (Common Information Model), which define the API (application programming interface) for EMS systems, are examples of domain ontologies and they were incorporated into the ee-district ontology. Different software vendors develop their own independent Energy Managament System (EMS) applications; therefore, the IEC 61970 was defined to support the integration of these various EMS applications, or distribution or generation management (aspects of power system operations). These APIs developed using these standards are therefore capable of accessing public data and exchange information regardless of how they are presented internally [50]. Because these standards are initially expressed as normative sets of UML packages, a transformation into sets of OWL2 ontology modules is required. Although not exemplified in this research, similar transformation/mapping efforts exist between the Industry Foundation Classes (IFCs) and the Semantic Web languages [51]. The IFCs specify a conceptual data schema and an exchange file format for Building Information Model (BIM) data. The conceptual schema is defined in EXPRESS data specification language [52]. The authors carried the model transformation task manually. It is worth mentioning that such a task can be automated using a model transformation tool, such as the ATLAS Transformation Language (ATL) [53] or the QVT languages [54]. It seems however that when the size and number of models to be transformed is still humanly reasonable, the overhead time and effort to learn/configure such a tool has to be pondered. Another ontology module is reused from the GeoSPARQL standard, the Geography module-an RDF/OWL vocabulary for geographic information, which is maintained by the Open Geospatial Consortium [55]. Domain ontologies are the most flexible part of the network of ontologies that supports the ee-district ontology, as they are a consequence of the requirements of the applications that will consume the represented knowledge. For example, in their smart grid information model, Zhou et al. also considered a weather ontology [2]. The different ontologies or ontological modules and their interdependence are depicted in Figure 6. The socio-technical system ontological module implemented by the authors follows the specification included in Koen van Dams Phd Thesis [44] and also relies on

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(a) topology, socio-technical (b) system

Figure 5: ee-district ontology links with (a) topology and socio-technical and (b) system ontologies.

OntoCAPEs Meta Model for the Design of Domain Ontologies [56]. The major extension to this Meta Model is that the ee-DIM aligns the target ee-district ontology with the domain-independent ontology modules (mainly system, topo-mereological and spatio-temporal modules) indirectly, by interposing the generic socio-technical system ontology. The duality social/technical aspects is express-ible in the proposed model, largely thanks to the reuse of the concepts from van Dams thesis [44]. Similarly to the transformation from one meta-model to another, and even though the authors carried the present alignment man-ually, the alignment of one ontology with another could be automatised [57]. Again, this possibility is to be considered thoroughly if and when the amount and the size of the ontologies to be aligned grow significantly. For the time being, it seems to be unnecessary, as the considered ontologies have all been handcrafted by researchers (OntoCAPE ontologies, the socio-technical system

Figure 6: Main groups of ontological modules supporting the ee-district ontology.

ontology) or experts (CIM ontologies, GML ontologies). Figure 5 shows UML
diagrams representing portions of the proposed network of ontologies focusing
on the re-use of upper level topology, socio-technical and system ontologies.
In these two diagrams, as well as in Figure 6, the representation follows the
mapping of OWL2 with UML from the Object Management Groups Ontology
Definition Metamodel [58]:

- OWL 2 ontologies are mapped with UML packages;

- OWL 2 classes are mapped with UML classes;

- OWL 2 subclassing is mapped with UML generalisation;

- OWL 2 property pairs are mapped with UML associations.

Finally, the screenshot of GraphDB's class relationships visualiser in Figure 7
shows the number of relationships that exist between instances of a selection
of ee-district classes (after the ontology has been populated with instances of
three specific real-world district case studies).

5. Preliminary validation of the ee-district ontology

The authors validated the developed ontologies ahead of using them, not
only in order to ensure that the ontologies are properly engineered, but also to

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Figure 7: Class relationships in the ee-district ontology once populated with real-world instances.

evaluate the adequacy to the final application (i.e. as the semantic backbone of software development for information management in district energy systems).

The first validation stage was performed thanks to existing automated tools.
W3Cs RDF/XML validator [59] and the University of Manchesters OWL validator [60] (both available online) were used to check the syntax of the ontology files.

The engine and rules integrated in TopBraid Composer [61] were used to

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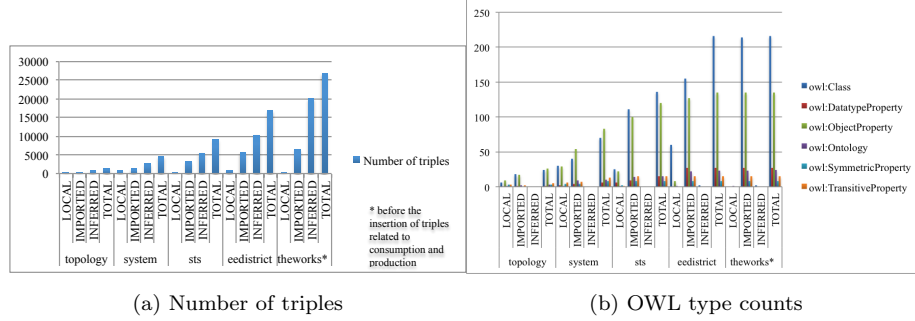(a) Number of triples   (b) OWL type counts

Figure 8: Number of triples and OWL type counts in the main ontologies of proposed district information model.

check the conformance to the OWL 2 RL profile [62] and generate the corre-
sponding inferred triples. Practical examples of inferred triple that are par-
ticularly relevant for this research include transitivity inferred triples. Topo-
logical and mereologico-systemic relationships are typically used by the ee-
district ontology. In particular, the socio-technical system ontology and the
ee-district define various sub-properties of the system:isConnectedTo and the
system:isSubsystemOf object properties. The transitive rule prp-tp (from the
TopBraid OWL RL inference rule nomenclature7) allows the inference of the
full structures of the networks involved a district energy system, starting from
the direct one-to-one relationships between the physical nodes and the physical
connections in the district. Another useful tool for the validation of the ontolo-
gies developed by the authors (ee-district) or implemented by them following
third-party specifications (socio-technical system ontology, CIM ontologies) was
the OntOlogy Piftall Scanner (OOPS) [63]. OOPS is an online tool that detects
design anomalies in OWL ontologies and provides natural languages reports
about the nature of the anomalies and suggestions to solve them. Some critical
anomalies that were spotted by the OOPS tool, are missing inverse properties
and defining domains or ranges of properties as intersections instead of unions.

The objective of the second stage of validation is to check whether the ontol-
ogy, once instantiated with knowledge from the case study presented in Section 2

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Table 3: Prefix names used in the algorithms.

Prefix name	Prefix IRI	Description
rdf:	`<http://www.w3.org/1999/02/22-rdf-syntax-ns#>`	Resource Description Framework (RDF)
system:	`<file:/C:/OntoCAPE/OntoCAPE/upper_level/system.owl#>`	OntoCAPEs system thinking ontology [46]
topology:	`<file:/C:/OntoCAPE/meta_model/topology/topology.owl#>`	OntoCAPEs topology ontology
sts:	`<http://www.nginfra.nl/socio_technical_system#>`	Ontology of socio-technical systems [44]
eedistrict:	`<http://www.resilient-project.eu/eedistrict#>`	Ontology of energy efficient districts
theworks:	`<http://www.resilient-project.eu/theworks#>`	District specific ontology

and queried with relevant SPARQL queries, is able to answer the competency questions listed in Tables 1 and 2. First, an ontology has been specifically created for the case studys district (the authors use the prefix name *theworks* for this ontology, Table 3 maps the prefixes with the prefix names used in this paper) by asking the district technical managers to fill template spreadsheets in order to collect knowledge and data. Then, components of the district energy system have been instantiated as instances of classes of the *eedistrict* ontology (in the OWL jargon, a named individual, featuring its URI, has been created for each district component). The specific ontology has been deployed into an ontology repository (OWLIM lite [64], now known as GraphDB Free). The repository itself is hosted in one of the virtual servers of the HPC cluster at the authors institute. As a direct reflection of the informal competency questions, a Java program has been implemented using the SESAME API [65] (OWLIM lite being an implementation of the SESAME specification). The programs inputs are the SESAME server and repository configurations and the URI of the instance of *eedistrict:DistrictEnergySystem*. The program runs all competency queries for all instances related to the given instance of district energy system. An example of how a competency question (in this case, List all the connections given a producer URI) translates into a SPARQL query can be found in Figure 9. The compactness of the SPARQL query is a result of relying on the expressivity of the abstract system and socio-technical system ontologies. Table 4 gives query times for the topological competency questions. Two series of query time measurement have been conducted with the querying program running on a desktop computer located in the same local network (LAN) and in a remote

```
SELECT DISTINCT ?conn
WHERE {
theworks:EnergyCentre_Boiler_4 rdf:type eedistrict:EnergySourceSystem.
?conn rdf:type edistrict:HeatingConnection.
?conn sts:from heworks:EnergyCentre_Boiler_4.
theworks:EnergyCentre_Boiler_4 system:isSubsystemOf theworks:DistrictEnergySystem_EbbwVale.
?conn system:isSubsystemOf theworks:DistrictEnergySystem_EbbwVale
}
```

Figure 9: Sample SPARQL query.

location (WAN). The query times are both a reflection of the small number of
output connections of generation units (they are generally directly connected to
a single aggregating energy system, e.g. a heat exchanger for heating generation
units or a switchboard for power generation units), and also of the relatively
more complex high-level topology of the heating network of the case study. That
led the authors to add a series of competency queries in the program, which were
not foreseen in the informal competency questions, e.g. List all heat exchangers
or List the heat exchangers connected to a given producer.

6. Architecture of the web service generator

As an information model, the ee-district ontology aims to express the core
knowledge required by any district-scale energy management software appli-
cation (monitoring, visualisation, generation/distribution control etc). It pro-
vides a high-level semantic representation of the district energy system com-
ponents and organisation. As schematised by Figure 10, the ontology is to be
encapsulated into a web service, which facilitates the consumption of knowledge
by various energy management software components by presenting a simple
HTTP/REST interface, rather than a HTPP/SPARQL protocol endpoint. The
web service requires a minimal understanding of the *eedistrict* ontology. The
code generation provides web developers with a convenient web service architec-
ture featuring access to essential concepts of the ontology. This automatically
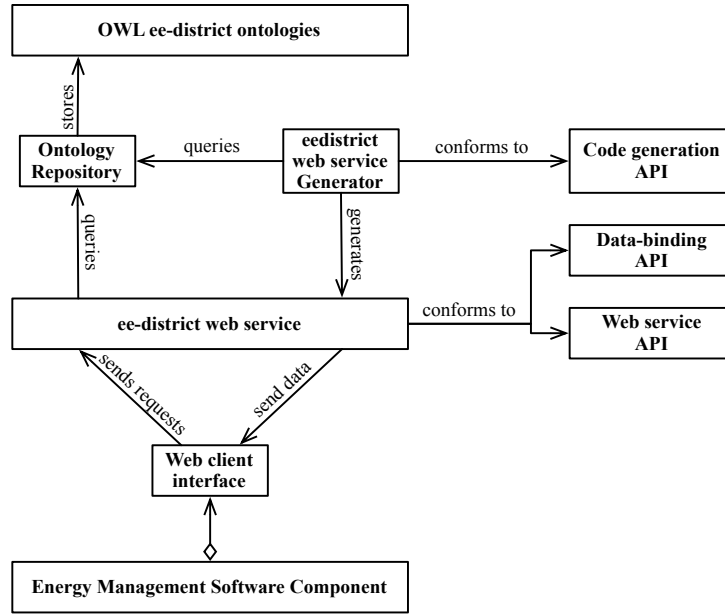
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Figure 10: Rationale of ee-district web service generation.

Table 4: Comparing query times over 10 runs.

	Average query time (ms)	
	LAN	WAN
List all heating connections given a producer URI	8.1	31.3
List all electrical connections given a producer URI	9.5	33.6
List all heating connections given a consumer URI	177.1	188.4
List all electrical connections given a consumer URI	77.8	87.4

generated infrastructure can then be extended with more encapsulations/relays of complex SPARQL queries, according to the requirements of the client components. Figure 11 illustrates the flow of various middleware environments that have been used by the authors to achieve a semi-automated ontology-driven con-
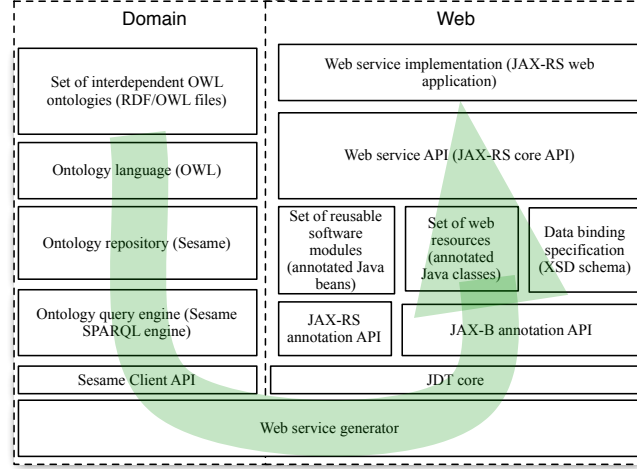
Figure 11: Architecture of ee-district web service generator.

struction of a web service, from the targeted domain of district energy systems to the implementation of a RESTful compliant web service. The generator implemented by the authors constitutes the flow substructure. The code generation

565 implemented in this research is an ad-hoc generation of source code as strings [66], facilitated by the source code manipulation functionalities of the Eclipse JDT infrastructure [67]. The end product of the generation process takes advantage of two Java specifications: the Java Architecture for XML Binding (JAXB) [68] and the Java API for RESTful Web Services (JAX-RS) [69] to facilitate the

570 definition of web service architecture. Eventually, the web service produced by the ontology-driven generator encapsulates the knowledge expressed in the ee-district ontologies. The code generation is therefore threefold:

- generation of the source code of the classes that encapsulate the ontology entities and their associated services;

575 - generation of the annotations of the source code that specify the web services; and,

- generation of the queries that are embedded in the code.

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http://XXXXXXXXXXXX/eedim/rest/building/LeisureCentre

○GET ○POST ○PUT ○PATCH ○DELETE ○HEAD ○OPTIONS
○Other [   ]

| Raw | Form | **Headers** |

[   ]

Clear   Send

Status   **200** OK ⓘ   Loading time: 1805 ms

Request   **User-Agent**: Mozilla/5.0 (Macintosh; Intel Mac OS X 10_9_5) AppleWebKit/537.36 (KHTML, like (
headers   Chrome/38.0.2125.101 Safari/537.36
                Content-Type: text/plain; charset=utf-8
                Accept: */*
                DNT: 1
                Accept-Encoding: gzip,deflate,sdch
                Accept-Language: fr-FR,fr;q=0.8,en-US;q=0.6,en;q=0.4
                Cookie: __utma=189758699.1603260990.1383755517.1383755517.1383755517.1

Response   **Server**: Apache-Coyote/1.1
headers   **Content-Type**: application/xml
                Content-Length: 586
                Date: Mon, 13 Oct 2014 13:58:48 GMT

| Raw | XML | **Response** |

Copy to clipboard Save as file

```
<?xml version="1.0" encoding="UTF-8" standalone="yes" ?>
<building>
  <uri>http://www.resilient-project.eu/theworks#LeisureCentre</uri>
  <inEdges>http://www.resilient-project.eu/theworks#heatPipe16</inEdges>
  <inEdges>http://www.resilient-project.eu/theworks#ElecConnection_9
  </inEdges>
  <isSubsystemOf>
  http://www.resilient-project.eu/theworks#Ebbw_Vale_District_heating
  </isSubsystemOf>
  <isSubsystemOf>
  http://www.resilient-project.eu/theworks#Ebbw_Vale_Electricity_System
  </isSubsystemOf>
  <isSubsystemOf>
  http://www.resilient-project.eu/theworks#DistrictEnergySystem_EbbwVale
  </isSubsystemOf>
</building>
```
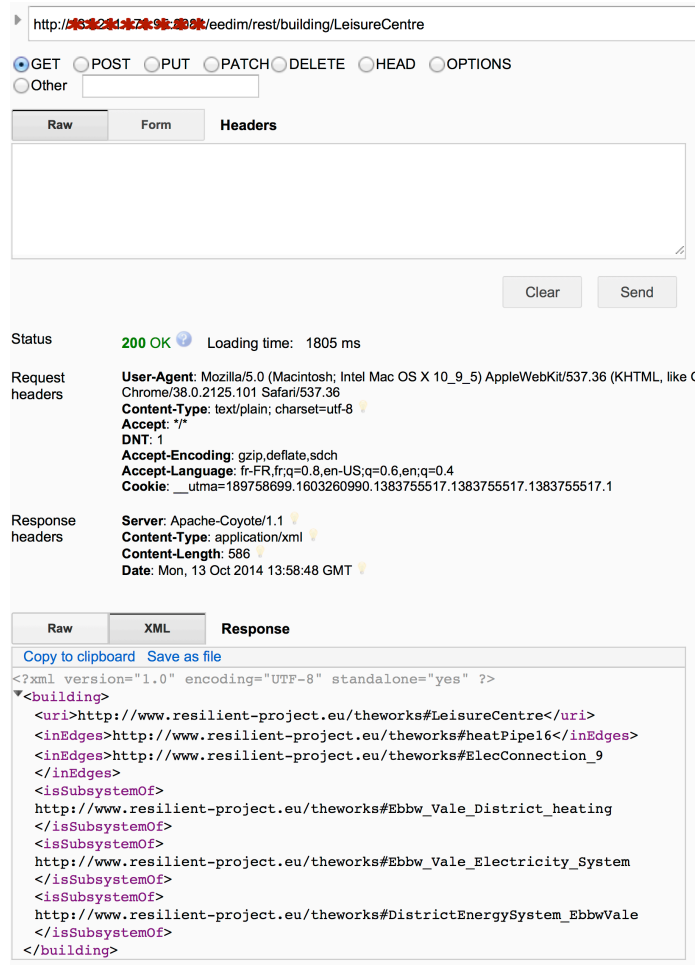
Figure 12: Example of HTTP request and response of a generated web service.

Figure 13 describes the overall process of generating the web services, leaving aside Eclipse JDTs and SESAMEs idiomatic constructs but rather reusing some of the formalism found in the W3C Recommendation that maps the structural definition of the OWL language with RDF graphs [70]. In summary, for each OWL class of the ee-district ontology subclassing the socio-technical system classes Node or Edge, a Javabean class and a service classe are created. Properties of the Javabean are created after the object and datatype properties for which the associated OWL class is domain. The type of a Javabean property

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depends on the range of the corresponding OWL property. It is another generated class if it's translating an object property or it is a built-in Java type corresponding to an XML built-in type if it's translating a datatype property (in both cases, the type of a property can also be the List interface parameterized with the proper generated class or built-in type). The key component of the service classes is the *findByURI* method that is the one that forges the proper SPARQL query and actually queries the underlying SPARQL engine. An example of a basic HTTP request to/response from a generated web service can be found in the screenshot of Figure 12. The SPARQL query that would normally be required in order to retrieve information about a building in the considered district energy system is encapsulated in a much more compact RESTful HTTP request and results in a plain XML (alternatively JSON) formatted answer. By forging a proper sequence of such HTTP requests, a client application can possibly:

- obtain some knowledge related to a particular node or connection;

- build an image of the entire topology of the local energy physical and social networks; and,

- obtain information about the mereological organisation of the district energy system.

7. Discussion

A number of academic works within the field of urban/district energy systems, have considered aspects of semantic modelling, such as van Dam [1] who states that ontologies have widespread use towards the interoperability of software models. Currently, this primarily manifests by facilitating agent interactions, such as Béhé et al. who designed a framework for the ontology-based specification of agent behaviors to build simulations of real systems [71]. The benefits of semantic modelling within energy systems typically center around interoperability of software components, with works such as Zhou et al. [2] stating

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```
RC repository configuration, NS target ontology namespace
SSC := {Class(sts:PhysicalNode), Class(sts:PhysicalEdge), Class(sts:SocialNode),
Class(sts:SocialEdge)}
JavaClass(connector), JavaClass(uri), JavaPackage(wsp)

Generate JavaPackage(beans) in wsp
   Generate JavaPackage(services) in wsp
   Copy connector in services
   For each supc in SSC
      For each subc s.t. SubclassOf(subc supc)
         Lprop := ∅
            Generate bean := JavaBeanClass(*:subc)
               Generate constructor := JavaBeanConstructor(*:subc) in bean
               Generate constant := JavaConstant(*:subc uri) in bean
               Generate member := JavaBeanMember(*:subc uri) in bean
               Generate getter:= JavaGetter(*:subc uri) in bean
               Generate setter := JavaSetter(*:subc uri) in bean
               For each prop s.t. ObjectPropertyDomain(prop subc)
                  Generate member := JavaBeanMember(*:prop uri) in bean
                  Generate getter:= JavaBeanGetter(*:prop uri) in bean
                  Generate setter := JavaBeanSetter(*:prop uri) in bean
                  Add (subc, Lprop ∪ {prop}) in MAP
               For each prop s.t. DatatypeProperty(prop subc)
                  Let dr s.t. DatatypeRange(prop dr)
                  Generate member := JavaBeanMember(*:prop JavaDatatype(dr)) in bean
                  Generate getter:= JavaBeanGetter(*:prop dr) in bean
                  Generate setter := JavaBeanSetter(*:prop dr) in bean
                  Lprop := Lprop ∪ {prop}
         AddEntry (*:subc, Lprop) in MAP
            Generate service := JavaServiceClass(*:subc)
               Generate member := JavaMember(*:subc) in service
               Generate getter:= JavaGetter(*:subc) in service
               Generate setter := JavaSetter(*:subc) in service
               Generate constant := JavaConstant(NS) in service
               Generate constructor := JavaServiceConstructor(*:subc) in service
               Generate constructor := JavaServiceConstructor(*:subc uri) in service
               Generate get := JavaGetMethod(service)
               Generate findByURI := JavaFindByURIMethod(service MAP)
```
, where:

- `*:x` is the IRI of named individual x;
- `JavaBeanClass` creates a Java class with a valid name derived from the provided IRI annotated with XML bindings;
- `JavaConstructor` adds a default Java class constructor with a valid name derived from the provided URI without arguments;
- `JavaBeanMember` adds a member variable with a valid name derived from the provided URI , with the provided Java type and annotated with XML bindings;
- `JavaDatatype` returns a Java type corresponding to the provided XML datatype;
- `JavaConstant` adds a constant declaration in the target Java class;
- `JavaGetter` adds a "get" method with a valid name derived from the provided URI in the target Java class;
- `JavaSetter` adds a "set" method with a valid name derived from the provided URI in the target Java class;
- `JavaMember` adds a member variable with a valid name derived from the provided URI and with the provided Java type;
- `JavaServiceConstructor` adds a default Java class constructor with a valid name derived from the provided URI with or without arguments depending whether a type is provided;
- `JavaGetMethod` adds a method that will respond HTTP GET requests;

and `JavaFindByURIMethod` adds a method that will query the ontology repository (using the same configuration/credentials as the generation program), in order to build the requested instance of the associated Java bean class, the response will contain the XML representation of the instance.

Figure 13: Web service generation algorithm.

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that information integration is essential for the next generation of smart grid applications. Ontological modelling itself has been studied since circa 1993 [72] and has been adopted successfully in several other scientific fields such as bioinformatics and medical information systems [73], which have inspired some energy system ontologies directly [74]. However, its use within urban modelling has been referred to as "embryonic" as of 2013 [73], in part due to early criticisms of its adoption [75] and alternative modelling techniques [76]. The field of semantic representations for UES management is very narrow in focus and equally immature, such that direct relevance is sparsely observed within existing reviews. Regardless, the works which were observed to describe the most relevant trends, developments and challenges are as follows:

- Abanda et al. [73] - a recent work which reviews developments in semantic web applications related to the built environment in general;

- Keirstead & van Dam [77] - whilst the authors specifically compare two ontologies, they utilize their experience to comment on the field as a whole;

- Zhou et al. [2] - the authors dedicate a significant portion of this paper to summarizing the current state of the field and the motivation for semantic modelling;

- Houwing et al. [6] - an early work arguing the application of socio-technical modelling within energy networks based on trends in the industry;

- Blöchle et al. [3] - a recent work which presents the preliminary results of an EU project aiming to develop a roadmap for ICT usage in energy efficient neighborhoods;

- Catterson et al. [78] - an early work which considers semantic interoperability between MAS solutions in a related field.

These works indicate an ongoing interest in pursuing the exchange of urban energy knowledge via ontologies. Additionally, it can be observed from several of

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these works that the challenge of integrating systems utilizing different ontologies could be mitigated through the development of an "upper" or "common" domain ontology, such as the one used in the design of the ee-district ontology as described in Section 4.3. This reiterates the need for substantial abstraction to be utilized in ontology development, as described in Section 4, in order for it to be extensible and to more easily integrate it with ontologies of different domains and perspectives. As mentioned, the main application of ontologies and semantic technologies in the field is in providing a common language for software components to communicate via, so as to promote interoperability across systems and domains. van Dam [1] extends this by expressing that a formalized data structure allows a common language between modelers as well as consistent software design and model interoperability. Further to this, Zhou et al. [2] advocate ontology based reasoning and data transforms, adding intelligence to the knowledge-base paradigm beyond simply using the semantic model as a supporting layer. Wang et al. [79] utilize semantics to support data integration in a semantic sensor service network. A final application is presented in relation to computing networks [80], [81], where ontologies can be utilized for resource description and discovery. In a closely related field to that considered here, ontologies have been utilized successfully to support building energy management [82, 83, 84, 85, 86, 87]. The ability to quickly produce and deploy web services based on shared domain ontologies, as exemplified in Section 6, would then greatly facilitate the development of supporting software that aim to interrelate intelligent sensing, data models and energy models with visualization, analysis and decision support tools. A systematic development work flow, abstracted by a shared domain ontology, would ultimately give rise to improved urban energy management systems by better cross-system integration through *lightweight, loosely coupled, platform and language independent web services[88].*

8. Conclusion

This paper has described the series of steps that led the authors from capturing knowledge related to a specific district energy system, conceptualizing this in the form of an ontology, to the deployment of a web service that is intended to unify the access to relevant knowledge by energy management software applications. A brief description of the real world case study has been given to specify the context to which this research relates. Then, the authors described their methodology to capture and to conceptualise the knowledge required by the domain application. This resulted in crafting an OWL ontology, the ee-district ontology, and the identification of a set of abstract or higher level ontologies, as well as a set of specific ontologies whose domains are correlated. The ontology has been validated against the informal requirements that emerged during the ontology development stage. The authors performed this validation by deploying the ontology into a SPARQL-enabled semantic repository, by populating the ontology with the case studys datasets, and eventually by translating the competency questions into SPARQL queries and checking the validity of the responses. Playing the role of a mediator by unifying the knowledge related to district energy management is the main objective of the ee-district ontology. A web service application that encapsulates access to the ontology repository and that presents an interface simpler than a SPARQL endpoint would conveniently facilitate the development and deployment of energy management applications (such as monitoring, simulation, optimization applications). The authors approach consisted in developing a semi-automated ad-hoc generation program as a substructure of the ontology dynamic software environment. The benefits of this program are two-fold: preserve the developers from the repetitive and time-consuming task of implementing a web service that matches the basic capabilities of querying the ee-district ontology and provide these developers with a source code for a dynamic web application that is both functional and extensible. Current work includes implementing the ee-district ontology and Web Services, to support local data access and shared semantic models for the energy simulation and manage-

ment systems developed by the RESILIENT consortium, in three district sites not only in Wales (Ebbw Vale), the site that served as a case study in this paper,

700 but also in Belgium (Hasselt) and in Italy (Savona), to (a) assess the energy and environmental benefits of the RESILIENT energy management solution and (b) stress-test and ensures that the proposed concept is replicable and scalable to different climatic areas. The targeted goal will be reduction of district fossil fuel energy demand and CO_2 emissions by a minimum of 20 %. Further work will

705 aim to integrate the semantic model and web service development framework prototypes into the deployment of a cloud-based infrastructure [89], which will allow semantically unified, collaborative and sustainable energy management at district scale.

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