Advanced Engineering Informatics 25 (2011) 547–558

Contents lists available at ScienceDirect

Advanced Engineering Informatics

journal homepage: www.elsevier.com/locate/aei

Sustainable building technology knowledge representation: Using Semantic Web techniques

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ARTICLE INFO

Article history:
Received 2 June 2010
Received in revised form 19 February 2011
Accepted 25 February 2011
Available online 23 March 2011

Keywords:
Sustainable building technology
Photovoltaic system
Knowledge representation
Ontology
Semantic Web

ABSTRACT

The global quest for sustainability in the exploitation of resources and the need for carbon foot-print reduction has resulted in the development of a large number of innovations and a huge amount of knowledge on sustainable building technologies. Unfortunately, users are being overwhelmed with information overload in this area such that it is difficult for them to make informed choices. The emergence of Semantic Web technologies, the next generation of Web technologies, promises to considerably improve representation, sharing and re-use of information to support decision-making. This paper explores the extent to which emerging Semantic Web technologies can be exploited to both represent information and knowledge about sustainable building technologies, and facilitate system decision-making in recommending appropriate choices for use in different situations. This is done by undertaking a literature review of emerging Semantic Web technologies and emerging innovations in sustainable building technologies. To demonstrate what can already be gained from the Semantic Web, a conceptual model for representing information about photovoltaic system, a major type of sustainable building technologies has been developed. The model is used to develop and test a prototypical ontology in Web ontology language representing knowledge in the photovoltaic system domain. The ontology has been extended to include Description Logics that provide a reasoning mechanism to facilitate system decision support.
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1. Introduction

Society and governments around the world are encouraging the development and use of innovative sustainable building technologies to improve the performance of buildings and mitigate the effects of climate change. This has resulted in the development of a wide range of different innovations with a large amount of information and knowledge on sustainable building technologies. Information and knowledge about these innovations are being made available to users through the Web to facilitate accessibility and use. Although the attraction of the Web lies in its simplicity and ease of accessibility [1], the share wide ranging nature of these innovations means that internet searches often overwhelm individuals and practitioners with millions of pages that they have to browse through to identify suitable innovations to use on their projects. Users are therefore unable to make informed choices and have to rely on specialists with experience on a limited range of innovations for advice. It has been widely acknowledged that the solution to this problem is the use of a machine-understandable language with rich semantics for some or all of the information on the Web [1–4]. This has led to the emergence of the Semantic Web, the next generation of the Web, which promises to considerably improve information representation, sharing, re-use and automated processing by software agents to make inferences [1–4]. Key to this, is the use of a common language or an ontology [5] for representing knowledge from different sources to facilitate decision-making. The aim of the work presented in this article is to explore the extent to which emerging Semantic Web technologies can be exploited to both represent information and knowledge about sustainable building technologies and to facilitate system decision-making in recommending appropriate choices for use in different situations. An overview of Semantic Web technologies and sustainable building technologies is presented. A conceptual model, developed to facilitate abstraction and representation of this information and knowledge is presented. The outcomes of the exploratory work that has been undertaken to identify and use various Semantic Web techniques and tools for the representation of knowledge and making inferences from the knowledge are discussed. The exemplar inferences discussed include inferences that facilitate the selection of photovoltaic systems and the selection of their corresponding suppliers.

2. An overview of Semantic Web technologies

The emergence of the World Wide Web (WWW) has brought exciting new possibilities in information access and electronic

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doi:10.1016/j.aei.2011.02.006

business. The WWW has grown to be the largest distributed repository of information ever created. Estimates reveal that the Web currently contains about three billion static documents and being accessed by over 500 million users from around the world [6]. Web content consists largely of distributed hypertext and hypermedia, accessible via keyword-based search and link navigation. Simplicity is one of the Web's major strengths and an important feature in its popularity and growth. It is this simplicity that has fuelled its wide uptake and exponential growth. However, it is this very simplicity that is hampering further growth and exploitation of the Web. The explosion in the range and quantity of Web content also exposes serious shortcomings in the hypertext paradigm [1]. It is increasingly difficult to locate required content through existing search and browse methods [1–3]. Finding the right piece of information is often challenging. Search engines can assist in finding material containing specific words, but it is very easy to get lost in the huge amounts of irrelevant material. Selecting the relevant material out of the million Web pages on the computer screen becomes a nightmare and manually unachievable as this requires users to read through a large number of retrieved documents to extract the right information. Currently it has been hypothesized that the solution to this problem lies in the 'invention' of the machine-understandable semantics for some or all of the information on the WWW. The realisation of such a Semantic Web requires developing techniques for expressing machine-understandable languages (or ontologies) and making them available on the Web.

According to the WWW Consortium [7], the goal of the Semantic Web is to allow data to be shared effectively by wider communities, and to be processed automatically by tools as well as manually. The vision of the Semantic Web is very ambitious and will require solving long-standing research problems in knowledge representation and reasoning, natural language computing, computer vision and agent systems [8]. However, considerable progress is being made in the infrastructure required to support the Semantic Web, particularly in the development of languages, tools for content annotation, design and deployment of ontologies. Although the realisation of the Semantic Web is still a long way into the future, our aim in the work presented in this paper is to explore the extent to which we can apply emerging developments in this area in order to provide decision support and recommendations of appropriate innovations in sustainable building technologies for use in a particular situation. Nonetheless, based on this exploratory study, some existing essential Semantic Web components have been implemented in developing a prototype ontology in the domain of photovoltaic system. The development of the prototype ontology was facilitated by the protégé-OWL editor. To demonstrate the usefulness of ontologies, some exemplar queries have been formulated, executed and results presented. This was undertaken through the use of Description Logics (DL). A key to the Semantic Web technology is an ontology language which is the subject of the ensuing section.

2.1. Ontology and Web ontology language

In the early 1990s, researchers in the Semantic Web recognised the need for an ontology Web language and several proposals for new Web ontology languages emerged. These included Simple HyperText Markup Language (HTML) Ontological Extensions [9], the Ontology Inference Layer [10] and DAML + OIL (DARPA Agent Markup Language + Ontology Interchange Language) [11]. The WWW Consortium set up a standardization working group in 2001 to develop a standard for a Web ontology language (OWL) having recognised that an ontology-language standard is a prerequisite to developing the Semantic Web. This resulted in the development of the OWL ontology-language standard in 2004 exploiting earlier work on OIL, DAML and DAML + OIL. A key feature of OIL is its basis in DL, a family of logic-based knowledge representation formalisms descended from Semantic Networks and KL-ONE [12] but that have a formal semantics based on first-order logic [13]. All these formalisms adopt an object-oriented model in which the domain is described in terms of individuals, concepts or classes, and roles or properties. For example, in the photovoltaic system domain, a particular system on the market may be called PS-EMS1. In this case, the concept could be "PhotovoltaicSystem", the individual is "PS-EMS1" and the role "isTypeOf" describes the relationship between the concept and the individual. In a strict object-oriented paradigm the term 'classes' is used for concepts, 'properties' for roles and 'instances' for individuals. DL can be used to create a knowledge-base. The formal semantics allows for the development of reasoning algorithms that can be used to make correct inferences and answer complex queries about a domain.

2.2. Ontology applications

The OWL is being used in fields as diverse as biology [14], medicine [15], geography [16], geology [17], agriculture [18], defence [19] and construction [20]. The application of OWL is particularly common in the life sciences where it is used by developers of several large biomedical ontologies such as Biological Pathway Exchange [21], Gene Ontology [22], Systematised Nomenclature of Medicine [23], the Foundational Model of Anatomy [24] and the US National Cancer Institute thesaurus on cancer terminology [25]. The main output of the TOronto Virtual Enterprise (TOVE) is a set of integrated ontologies for the modelling of both commercial and public enterprises developed at the University of Toronto [26]. The TOVE project ontology is one of the best that defines the role or workers or agents in an organisation or an enterprise [26]. The Dutch government has several ontology driven applications on the internet that inform the public about rights and duties that are relevant for certain life events [27]. Some examples of life events are "the death of a close relative" and "working and studying" [27]. In Australia, efforts to structure various biological databases into a single representation format and to represent the mapping between various biological information using the power of OWL and Extensible Markup Language to discover data semantics in complex biological data known as BIOMAP Project is currently being undertaken at Murdoch University [28]. Most ontologies are typically developed through collaborative endeavours within a given community aimed at facilitating information sharing and exchange. This is certainly the case with the Industry Foundation Classes (IFC) and its associated ifcXML by the buildingSMART initiative [29] and the derived Web ontology language (ifcOWL) [20] in the construction industry for application in the building information modelling domain. In the following section we discuss the sustainable building technologies domain and the prototypical ontology being developed to explore the potential application of the Semantic Web techniques in this area.

3. An overview of innovations in sustainable building technology

There exists a broad range of products that fall within the sustainable building technology domain. There are many different characteristics which products may exhibit to demonstrate a degree of sustainability. Some products may be capable of being installed or assembled on site with minimum impacts on the environment. Some may be more energy efficient. Some may eliminate the use of fossil fuels. Some may include high proportions of recycled materials. Some may use natural sustainable materials. Some may promote water efficiency and some may reduce carbon emissions. These include materials, components and systems for off-site manufacture (steel frame, timber frame, structurally insulated panels, etc.), natural building materials (such as straw-bale, strawboard and rammed earth), energy efficiency technologies including renewable energy technologies (such as wind turbines, photovoltaic systems, geothermal systems and air source heat pumps), water conservation and sustainable urban drainage systems (such as rainwater harvesting, grey water recycling, green roofs and porous pavements), waste minimisation (recycled wall ties, recycled kitchen units, etc.), etc. A wide range of innovative sustainable building technologies are emerging in response to the global quest for sustainability in the exploitation of natural resources and the need for carbon foot-print reduction in response to climate change. Many suppliers now boast of having a wide range of products in the order of several thousands in their catalogues. A great deal of knowledge and understanding of these innovations is required to be able to make the right choices to use in particular situations. This presents potential clients and users with significant challenges in selecting the right products to suit particular uses, especially in areas of emerging technologies. These catalogues have traditionally been produced in book form but are increasingly being made available through the Web. The Web has improved accessibility to users but as earlier alluded to; even a simple search of a particular innovation will produce millions of pages through which a user needs to read. Even where a user has knowledge of a particular type of product, it is not possible to issue even the simplest of queries to identify product instances that meet their particular requirement. This makes this particular area suitable for exploration for the potential application of Semantic Web techniques to help users locate specific products that meet their particular needs. This is the goal of this work. In a research endeavour of this nature with limited resources, it is not possible to tackle the full range of products available. We will use a subset of the technologies available for exploratory reasons and hope to develop insights that can be applicable to the full range of sustainable building technologies. We have chosen to focus on photovoltaic systems as they are currently generating a lot of interest in the domestic building area with high public visibility.

3.1. Photovoltaic systems

Photovoltaic cells are semiconductor devices which convert energy in sunlight directly into electricity. Individual cells only generate low voltages and currents, so they are usually grouped in rectangular ‘modules’ that comprise a transparent cover, a metal mounting frame and a backplate, thus forming a weatherproof enclosure. Modules are often grouped into arrays. Photovoltaic cells can also be moulded into solar slates or solar tiles for integration into roofs, or bonded onto glass or metal sheets for incorporation into architectural glazing and fascia systems. Various types of photovoltaic systems use different semi-conductor materials and manufacturing techniques. Photovoltaic system installations have a wide variation in outputs and are thus rated according to their peak power output (kWpeak or kWp). Photovoltaic system can be grid-connected or they can be stand-alone. A typical ‘grid-connected’ system allows the installation to put power into the building mains electricity supply in parallel with the local grid. When the building demands more electricity than the photovoltaic system can provide, the grid provides the ‘top-up’. When the photovoltaic system is generating more energy than the building needs, the excess is exported to the grid. For illustrative purposes, a simplified grid-connected photovoltaic system diagram depicting its main components is presented in Fig. 1. The key component in such a system is the inverter, which converts the direct current (DC) generated by the photovoltaic system into alternating current (AC), and does so in synchrony with the mains. Grid-connected systems require very little maintenance, are generally limited to ensuring that the panels are kept relatively clean. The wiring and components of the system need to be checked regularly by a qualified technician. Stand-alone systems, i.e. those not connected to the grid, need maintenance on other system components, such as batteries. Prices for photovoltaic systems vary, depending on the size of the system to be installed, type of photovoltaic cell used and the nature of the building on which the photovoltaic system is mounted. The size of the system is dictated by the amount of electricity required.

4. The development of the photovoltaic systems ontology

4.1. Conceptual modelling of the photovoltaic system ontology

A pre-requisite to developing a Semantic Web-based application is the establishment of an ontology for the application domain. There are many groups developing ontologies in different application domains as previously indicated. Where ontologies already exist for a domain, it may be simply a case of adopting one or more of these and extending and enriching them where necessary. We are not aware of the existence of an ontology in the photovoltaic system domain so we have had to develop one. Our approach was to start by undertaking an abstraction of the concepts that characterise a photovoltaic system. The concepts that characterise any ontology domain should reflect the purpose of the ontology, what the ontology is intended to support or the requirements to be attained by the ontology [30]. The main purpose of the ontology in this paper is for clients to be able to select photovoltaic systems for use in different applications. Although it is possible to define the ontological concepts to represent the different photovoltaic systems and suppliers, the selection process involves some intermediary processes that are challenging. For instance, the selection process involves the use of different criteria to distinguish between

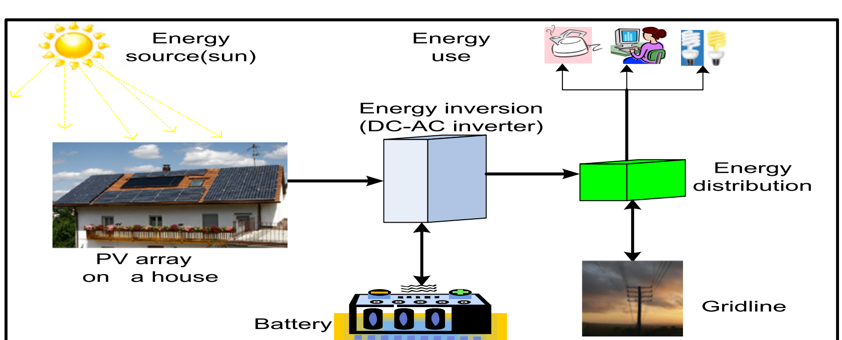

Fig. 1. Simplified grid-connected photovoltaic system.

the different photovoltaic systems available. This means that at some stages, practitioners are constrained by the selection criteria which they use to make decisions whether to choose a photovoltaic system component/supplier or not. In some circumstances, computations are conducted. The establishment of the different intermediary processes and decision points in the selection of photovoltaic systems can be achieved through the use of process models. Process modelling enhances the visual representation, the work processes and identifies problem areas and opportunities for process improvement [31]. To capture all the key processes involved in the selection of photovoltaic systems, process modelling was used. Process modelling is examined in Section 4.1.1.

4.1.1. Photovoltaic system ontology requirement considerations

In order to establish the ontology requirements, we consulted the literature on photovoltaic systems from various sources to undertake the abstraction and held discussions with a manufacturer of photovoltaic systems. The outcome of this activity led to the establishment of a process model (Fig. 2) that depicts the information and steps involved in the selection and acquisition of photovoltaic systems. This process model facilitated the abstraction of process concepts (see Section 4.1.2) which could not have been straightforwardly captured. Some examples are the "rough sizing of PV-modules" and the "sizing and selection of other components" as depicted in Fig. 2.

The selection process starts with the establishment of the client's requirements. In this phase the nature of factors such as sufficient sunlight, angle of tilt, roof size, building and tree sheds are established. If these factors are favourable, then a decision is made on whether to choose a grid or non-grid connected system. After this choice is made, the building energy load is computed using either past bills or from the power rating of household appliances. The building load is used in computing the sizes of the required PV-module. Based on the computed PV-module size and the building energy load, the size of the inverter and the battery are also calculated. The market PV-modules, batteries and inverters are selected

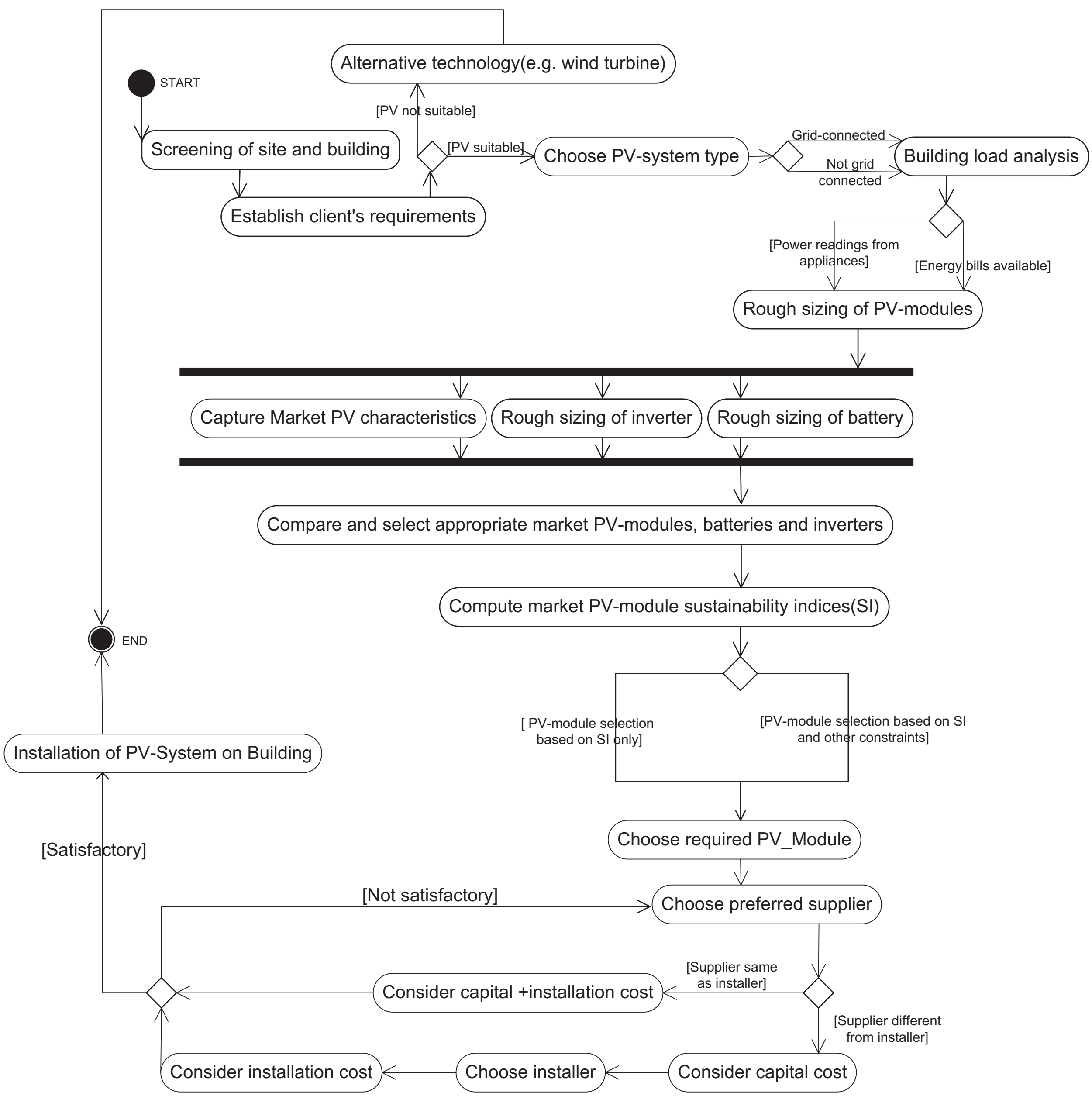

Fig. 2. Process model for the selection of photovoltaic system.

to match the computed sizes of the PV-module, battery and inverter. The sustainability indices of the selected market PV-modules are computed. These indices are computed by aggregating and normalizing the data-type properties of the market PV-modules. The details of this computation are out of scope of this paper and will be the subject of a separate publication. Based on the aggregated values, decisions can be made on selecting the different PV-modules by using only the sustainability indices or using these indices alongside other constraints. A PV-module and a preferred supplier are chosen. If the preferred supplier is also an installer, the client might want to consider both the capital cost and the installation cost. If the preferred supplier is not an installer, then the client might want to consider only the capital cost and the installation cost after having selected a preferred installer. If the client is satisfied then they can procure the PV-system but if not, the client can proceed to the selection of an alternative supplier.

4.1.2. The abstraction of knowledge models from the process model

Although "rough sizing of PV-modules" and the "sizing and selection of other components" were not captured as main ontological concepts or classes, they were used in describing ontology restrictions not often visible in ontology hierarchies. For instance a restriction on the size of a PV-module is "PV-module hasModuleSize <2.3 m^2". This restriction can be used in selecting PV-modules based on the size criteria. Furthermore, the process model of Fig. 2 laid the foundation to the establishment of two ontological components which are key to the photovoltaic system ontology. These are the ontological classes and their attributes. Based on the information flows in the process model, the Unified Modelling Language (UML) was used to create a semantically rich class diagram to allow us to graphically represent and visualise the concepts and relationships between them. The class diagram is depicted in Fig. 3. The class diagram depicts four top level concepts which include the *PhotovoltaicSystem*, the *Building*, *Organisation* and the *HouseholdAppliance* concepts. The details of how these concepts were established and their relationship to each other are examined in the ensuing paragraphs.

The PhotovoltaicSystem is made up of its components. A photovoltaic system component part can be a module or a combination of modules into a module panel, sub-array, array, or an array subfield. The non-photovoltaic components consist of what is termed the balance of components which themselves are the electrical and mechanical components shown in Fig. 1. Fig. 1 also shows that a photovoltaic system can be grid-connected or non-grid-connected. A non-grid-connected system can be a stand-alone DC, a standalone DC–AC, or a hybrid of both. As a photovoltaic system is a building component, the object properties relating both are *isContainedIn* and with inverse *hasContent*. This relationship reads naturally as PhotovoltaicSystem *isContainedIn* a Building while Building *hasContent* a PhotovoltaicSystem.

While clients are interested in knowing the different types of photovoltaic systems available in the market, they may also be interested in knowing who the suppliers are and the different installers who can install the different photovoltaic systems. Therefore, there is a need to consider a higher level concept that captures the *Supplier*, the *Installer* and the *Client* as sub-classes.

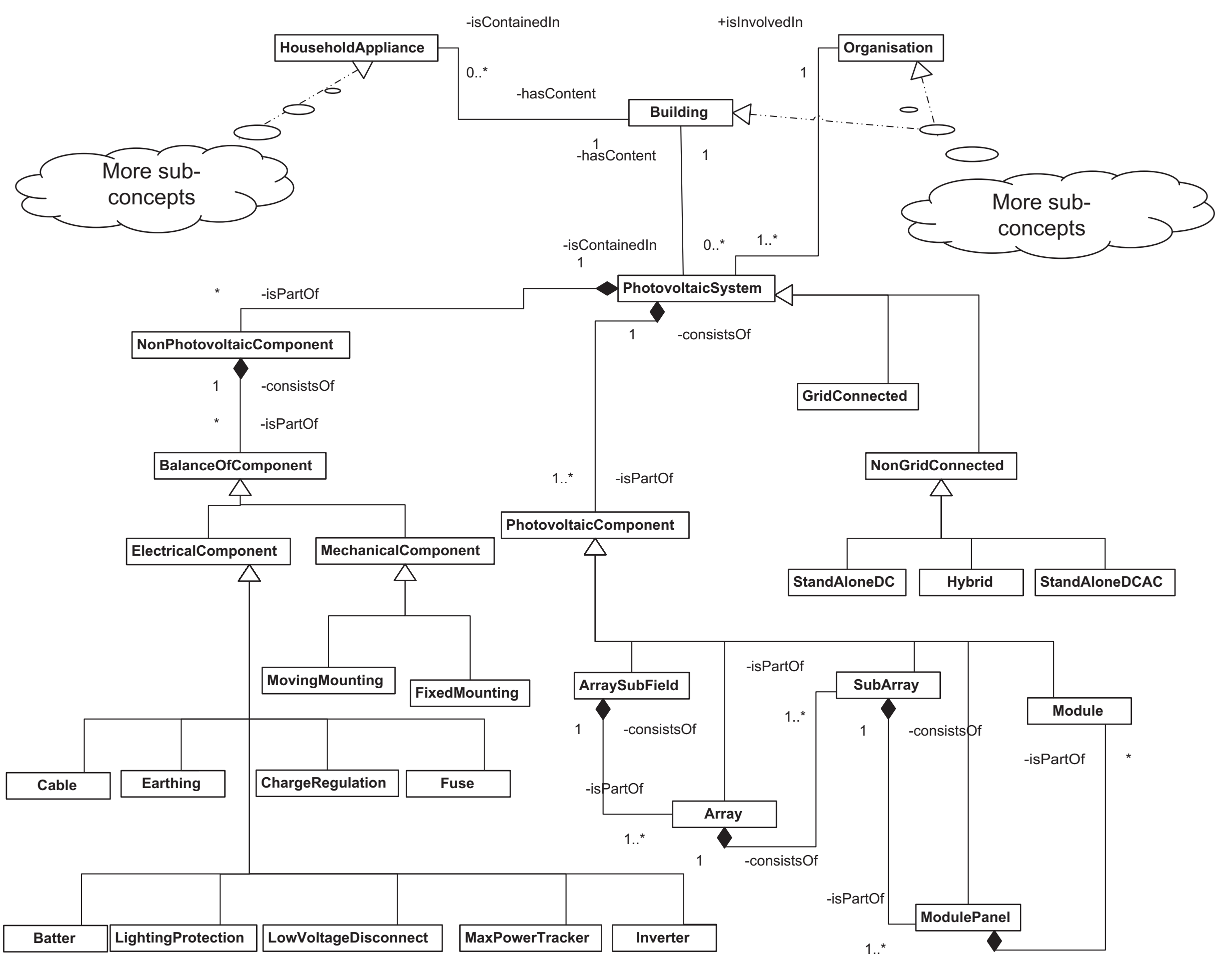

Fig. 3. The photovoltaic system UML class diagram.

Based on the literature review the *Organisation* ontology, an output from the TOVE project [26] was used. In the TOVE project, an organisation is an agent that plays one or more roles. The *Organisation* concept is related to the PhotovoltaicSystem concept through the object property *isInvolvedIn* and reads more naturally as an Organisation *isInvolvedIn* a PhotovoltaicSystem.

Furthermore, suppliers may require information about the building that a client requires a photovoltaic system for. Examples of such information include building address, building surroundings, building orientation and roof tilt. Therefore there is need to capture the "building concept". Recently, significant advances have been made in the development of interoperable Building Information Modelling (BIM) compliant languages that cover building objects. Two of these BIM compliant languages are Industry Foundation Classes (IFC) and CityGML. While the IFC model describes project information such as building elements, geometry and material properties, costs, schedules and organizations [32,33]), CityGML defines the geometry, topologies, appearance, and semantics of urban objects including buildings for modelling and exchanging virtual 3D city models to support such applications as urban planning and simulation, facility management and disaster management [34]. Although IFC and CityGML both model information about buildings, they both differ in the richness of their data content. While CityGML represents objects information at the scale of a city, the IFC model represents object information at the building level with great amount of detail and richness [33]. Like CityGML that has re-used the IFC building concept [33], the IFC building component was re-used. The *Building* concept defines the physical space in which the sustainable building technologies are being applied. Also the supplier may be requiring information about the energy consumption level of the client's building. Therefore, the household appliance concept was included in the ontology. The household appliance concept captures knowledge about the various domestic energy appliances in the UK houses [35]. The HouseholdAppliance and the Building concepts are related through the *isContainedIn* and *hasContent* properties. The relations are read more naturally as the HouseholdAppliance *isContainedIn* a Building and a Building *hasContent* HouseholdAppliance.

Although the organisation, building and household appliance concepts adopted in this study were not purposely developed for the photovoltaic system domain, they however provide generic knowledge concepts in which other knowledge models could be built or added as leaf nodes (extensions). This means their ontology components (i.e. data properties and instances) may not be complete for the purposes of the photovoltaic system ontology. We therefore investigated the different data properties and instances that can be used in enriching the photovoltaic system domain so that it is able to support decision making in the selection of different options.

4.1.3. Enrichment of the photovoltaic system conceptual model to include ontology components

One of the main reasons for undertaking this study is the information overload on the current Web on sustainable building innovations such as photovoltaic systems. This means that real-world examples of websites that contains photovoltaic system domain knowledge will constitute good sources of information for possible extraction of properties for enriching the semantic concepts developed above. Based on the literature, review the Green Book Live website [36] with links to other websites was chosen. The Green Book Live is a free online resource designed by UK Building Research Establishment which can help specifiers and end-users identify products and services that can help to reduce their impact on the environment. The quantitative and qualitative content analysis approach was used to analyse the information from the website. Quantitative or qualitative content analysis approach is defined as an approach for the analysis of texts and documents in which researchers seek to quantify/qualify content in terms of pre-defined categories in a systematic and replicable manner [37–39]. In using the quantitative/qualitative techniques in the elicitation of the properties of photovoltaic system components, some semantic problems were encountered. Problems such as word synonyms emerged, e.g. synonyms like peak power output, operating power output and maximum power output used by various suppliers to denote nominal power output of PV-array module were coded with the same code as nominal power output and nominal power output was adopted as the data type property in the ontology. Another finding from the Green Book Live database was that of suppliers providing more PV-array properties than others. Thus, it was imperative to semantically validate the captured properties concepts extracted from the Green Book Live database. The techniques of Noy and Musen [40] and the Logical Product Modelling techniques [31] were employed. The following example illustrates an example of a case where two suppliers specified a PV-array differently. The suppliers will be given anonymous names Supplier A and Supplier B.

Supplier A: PV-array A = {name, id, energy efficiency, warranty}.

Supplier B: PV-array B = {name, id, energy efficiency, CO_2 saving, cost saving}.

According to [31,40], the data properties to be considered should be the union (∪) of both specifications of the two suppliers as shown below.

PV-array A ∪ PV-Array B = {name, id, energy efficiency, CO_2 saving, cost saving, warranty}.

By adopting the techniques of [40] and the Logical Product Modelling techniques [31], semantically rich knowledge constructs relating ontology components of the photovoltaic system was developed. The semantically valid constructs are used to complement the main top level knowledge constructs which include the "Building" [33,41], "Household Appliance" [42,43]; and "Organisation" [36] concepts. The photovoltaic system concept is based on published and widely acknowledged technico-physical components that enable its functionality on a building [43].

The semantically enriched knowledge models provided us with the basis to implement an initial prototypical ontology in an ontology development environment to allow us to undertake experimentation and exploration of Semantic Web techniques as discussed in Section 4.2. The key to the exploration is the understanding of the mapping between UML knowledge models and the OWL. The mapping rules developed by [44–46] which cover all the UML and OWL ontology concepts were adopted.

4.2. The prototype design and implementation of the photovoltaic system ontology

The implementation of the prototype ontology required us to choose an appropriate ontology editor and development environment. The growing interest in the Semantic Web has stimulated an exponential growth in the development of ontology editors based on different ontology development methodologies. There exist different ontology development methodologies in the literature [47]. The challenge lies in the choice of a methodology and hence tools used in building the ontology. Furthermore, in making any choice, an ontology engineer is often guided by the prime purpose and the knowledge model of the ontology. The photovoltaic system ontology is intended to serve as a knowledge-base where intelligent searches about the various photovoltaic systems, their properties, application, suppliers, installers and cost implications can be determined. In designing such a knowledge-base a balance must be established between the simplicity and complexity of the knowledge models and the amount of information in the domain of discourse [47]. Based on the purpose of our photovoltaic system ontology and on a review of various ontology editors [48], the Protégé development platform which contains the Protégé-OWL ontology editor for the Semantic Web was chosen for use in this study. It is compliant with the OWL standard recommendation of the W3C as indicated earlier. Furthermore, unlike other editors (e.g. protégé-frame editors) protégé-OWL can efficiently deal with most object-oriented concepts captured in Fig. 3. Two of these concepts are composition relationship (not easily or straight forwardly modeled in protégé-frames) captured in Fig. 3 and transitive relations which cannot be dealt with in protégé-frames [49]. Another major advantage of OWL over other ontology languages such as the Resource Description Framework is the ability to detect anomalies in the ontology or in the set of instances in the ontology [2]. Common anomalies include violation of the subsumption concept, instance checking, ontology inconsistency. These anomalies are described below.

- *Concept subsumption:* Given an ontology O and two classes A, B, verify whether the interpretation of A is a subset of the interpretation of B in every model of O;
- *Instance checking:* Given an ontology, an individual a_1 and a class A, verify whether a_1 is an instance of A in every model of the ontology;
- *Inconsistency:* An example of an inconsistent error is the occurrence of partition errors or violation of the disjoint axiom. There are several ways of classification depending upon the type of decomposition of a super-class into subclasses. When all the features of subclasses are independently described and subclasses do not overlap with each other than it leads to disjoint decomposition (i.e. the disjoint axiom is respected). When the subclasses overlap, it violates the concept of disjoint axiom and easily leads to inconsistencies.

Another feature of OWL is its existence in three different dialects supporting varying levels of expressive capability [50]. These are OWL-Lite, OWL-DL and OWL-Full. OWL-DL was chosen because of its richer expressive power than OWL-Lite, and the fact that it supports automatic reasoning while OWL-Full does not [50]. Furthermore, the availability of user-friendly plug-ins with a scalable architecture in Protégé-OWL is an added advantage. Protégé-OWL supports DL reasoning through the use of the DL QueryTab, a plug-in which can be incorporated into protégé to support inferencing. OWL ontology consists of individuals, properties and classes. The protégé-OWL editor is used in modelling the UML model in Fig. 3. For clarity, a screenshot of the implemented knowledge model is presented in Fig. 4.

4.2.1. Reasoning with the photovoltaic system ontology

A major reason for developing an ontology is to represent knowledge about a specific domain so as to enhance the reasoning and acquisition of knowledge from the domain. Amongst the many ontology languages that are used in knowledge representation, OWL is the most prominent in the ontology research community. Like most ontology languages OWL makes it possible to describe concepts in a domain, but it further provides new facilities that can enhance reasoning. It has a rich set of operators such as intersection, union, negation and property restrictions. Using these operators complex concepts can be built from very simple ones.

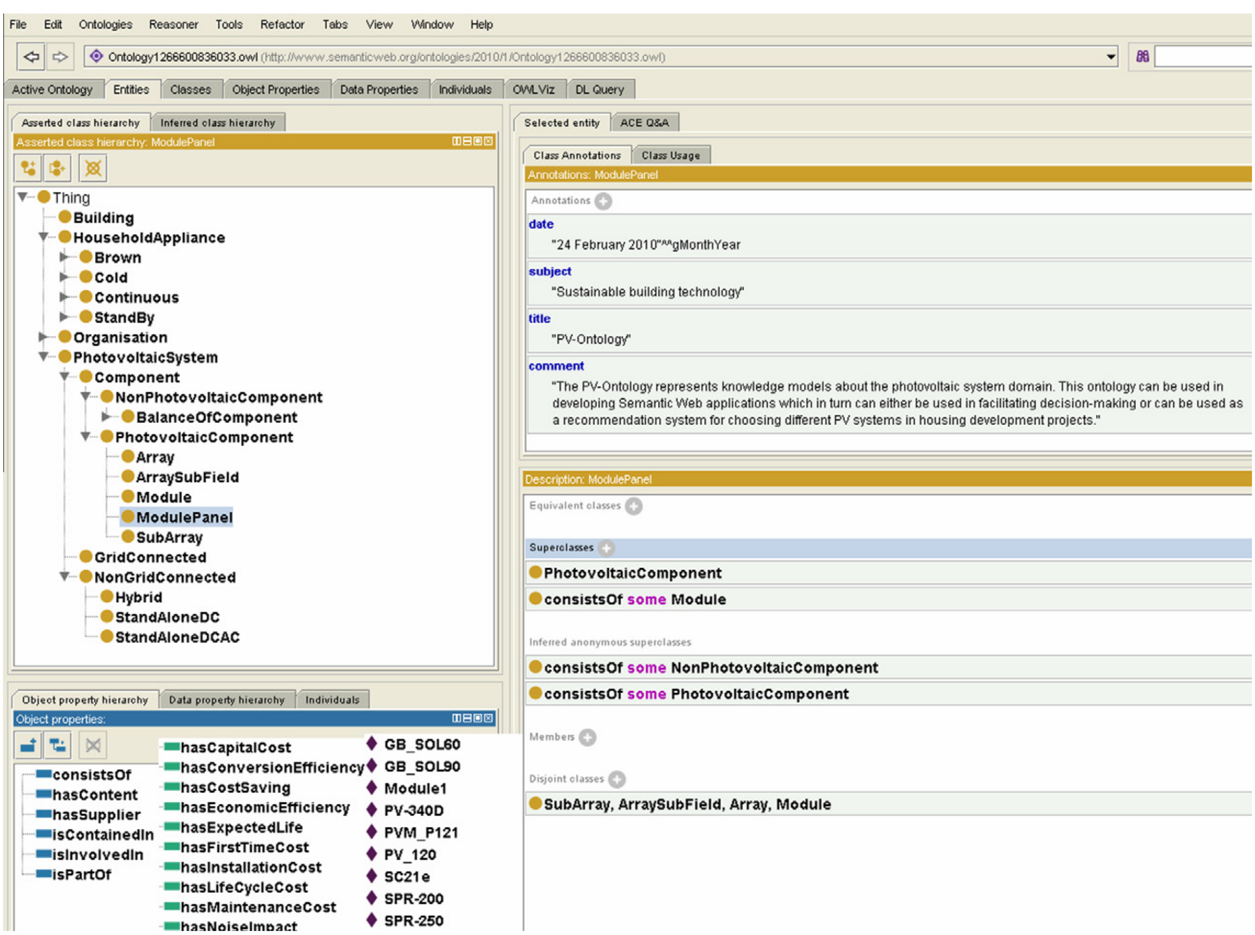

Fig. 4. A screenshot of protégé-OWL 4.0.2 containing the photovoltaic system ontology.

The union, intersection, negation operators and property restrictions form the foundation of the DL and have been used in many logic applications. The use of these operators in the formation of queries to interrogate any ontology is facilitated by the use of the DL Query plug-in in protégé-OWL [51]. The ensuing section examines the DL Query syntax easily edited using the DL QueryTab in protégé-OWL and demonstrates its use in interrogating the photovoltaic system ontology.

The DL Query provides a powerful and easy-to-use feature for interrogating a classified ontology. The query language supported by the plug-in is based on the Manchester OWL syntax [51]. This syntax is very user-friendly for OWL DL that is fundamentally based on collecting all information about a particular class, property, or individual into a single construct called a frame. One main advantage of the Manchester OWL syntax is the fact that it is easy to write and understand queries particularly to non-logicians. This is because it adopts an infix syntax rather than a prefix or postfix syntax. In computer programming an infix notation is the common arithmetic and logical formula notation, in which operators are written between the operands they act on (e.g. 2 + 2). Similarly in a prefix notation , the operator is written before the operands (e.g. + 2 2) or postfix in which the operator is written after the operands (e.g. 2 2 +). Furthermore, the DL special mathematical symbol (e.g. ∀, ∃ representing the universal and existential quantifiers) are represented using a simple natural language as *only* and *some* respectively. This infix syntax renders the DL syntax more natural and easier to read especially to non-logicians. An example of a Manchester OWL syntax is the use of the maximum cardinality often written maxCardinality between the property "hasConversionEfficiency" and the range of possible values that can be assumed by the conversion efficiency of a photovoltaic system (often a compact interval of [0, 1]). This is written as "hasConversionEfficiency *max* 1". This reads more natural in English language as a complete sentence can easily be formed from it as "An instance of a photovoltaic system hasConversionEfficiency *max* 1" to mean that the maximum conversion efficiency of an instance of a photovoltaic system cannot exceed 1. The infix syntax is easier to read than the conventional prefix and postfix style often adopted in most programming languages. Examples drawn from the photovoltaic system domain to illustrate the application of the most common infix syntax from the Manchester OWL syntax are presented in Table 1.

The implementation of the above syntax in modelling queries in the DL Query can be used in making important decisions by those interested in the domain of photovoltaic systems. The ontology-driven approach provides the flexibility for users to construct queries to meet their particular interests within the scope of the ontology developed. An advantage of the ontology-driven knowledge-based approach over traditional software is that it allows users to undertake queries to obtain answers that need not necessarily have been anticipated at design time. In general, the DL query syntax provides capabilities for handling constraints on properties or parameters modelled in an ontology. Given the flexibility in generating a wide range of different DL queries using different combinations of DL query constraints, different queries can be constructed and used to search for solutions that meet particular user needs. Three queries are presented in Figs. 5–7 for illustrative purposes. These have been chosen to illustrate the degree of complexity in query construction starting with the simplest in Fig. 5 with a single constraint to the more complex in Fig. 7 with four constraints as explained in the ensuing paragraphs.

In the first example, a construction professional may be interested in knowing the types of photovoltaic systems supplied by a particular company, say Solar_Century. This is achievable by writing and executing the query modeled in query pane of Fig. 5 in the DL query pane.

By ticking the instance box of Fig. 5 and executing the query, five instances are obtained from the knowledge base. The five photovoltaic system instances meet the requirement of being supplied by SolarCentury_UK.

In the second example, a user may be interested in knowing all photovoltaic systems with module efficiency in a given range and with the capital cost of the photovoltaic system in a given range. This can be formulated as in Fig. 6.

By ticking the instance box of Fig. 6 and executing the query, an instance is obtained from the knowledge base. The photovoltaic system instance meets the requirement of having a capital cost of less than 2000 monetary units and a conversion efficiency of more than 0.9.

The third example is about a client who wants to buy a photovoltaic system for use in his 3-bedroom semi-detached house. The client is looking for the best photovoltaic system supplier. The client is not willing to pay more than £2500 for a photovoltaic system module. The client is not also willing to travel beyond a given radius; in this case s/he does not want to travel out of his/her post code zone. The client's roof is not big enough and he is advised to purchase a smaller photovoltaic system module. A DL query can be modeled to provide results meeting the requirements of the client using some of the Manchester OWL syntax. This is represented in Fig. 7.

To facilitate understanding, the query in Fig. 7 can be broken down into four sub queries. It is important to note that the best photovoltaic system suppliers have been defined arbitrarily as those with the sustainability index values greater than or equal to 0.9. Sustainability index is one of the data-type properties defined in the ontology. In order to meet the clients first condition the query "BestModuleSupplier and hasSustainabilityIndex some float [⩾0.90] is executed. The output is a list of suppliers with sustainability index values of greater than or equal to 0.90. Secondly, based on the client's inability to pay more than £2500, the cost constraint is added. This is represented in DL as hasCapitalCost some [<2500]. This filters the results and only suppliers with cost less than £2500 are released as outputs. Thirdly, the client's post code is used to define his/her maximum travelling distance to

Table 1
Manchester OWL syntax.

OWL	DL symbol	Manchester OWL syntax	Examples
someValuesFrom	∃ (applicable on classes)	*some*	hasMechanicalComponent *some* FixedMounting
allValuesFrom	∀	*only*	hasMaterialType *only* Monocrystalline
hasValue	∃ (applicable on instances)	*value*	hasSupplier *value* SolarCentury_UK
minCardinality	⩾	*min*	hasDimension *min* 1.9 m^2
cardinality	=	*exactly*	hasWarranty *exactly* 25 years
maxCardinalty	⩽	*max*	hasConversionEfficiency *max* 1
intersectionOf	Λ	*and*	NonGridCoonected *and* Hybrid
unionOf	∨	*or*	StandAloneDC *or* StandAloneDCAC
complementOf	¬	*not*	*Not* GridConnected

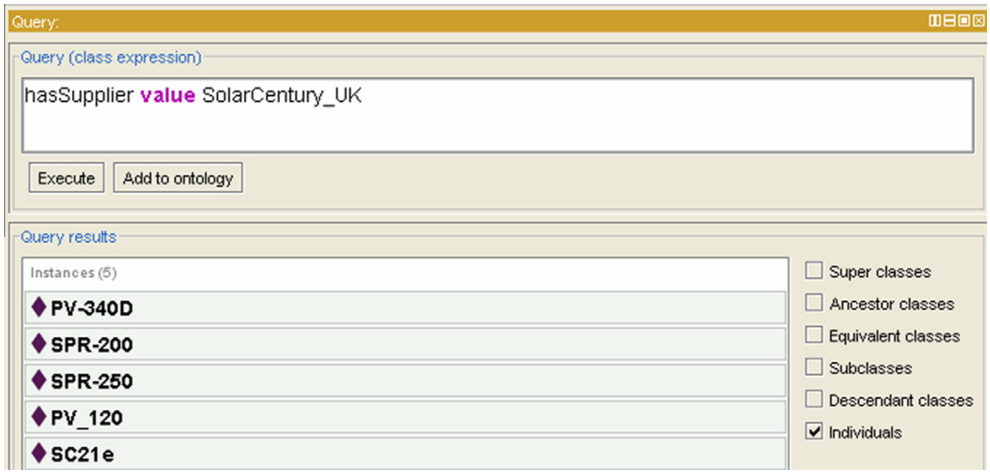

Fig. 5. Determination of instances of photovoltaic systems produced by SolarCentury_UK.

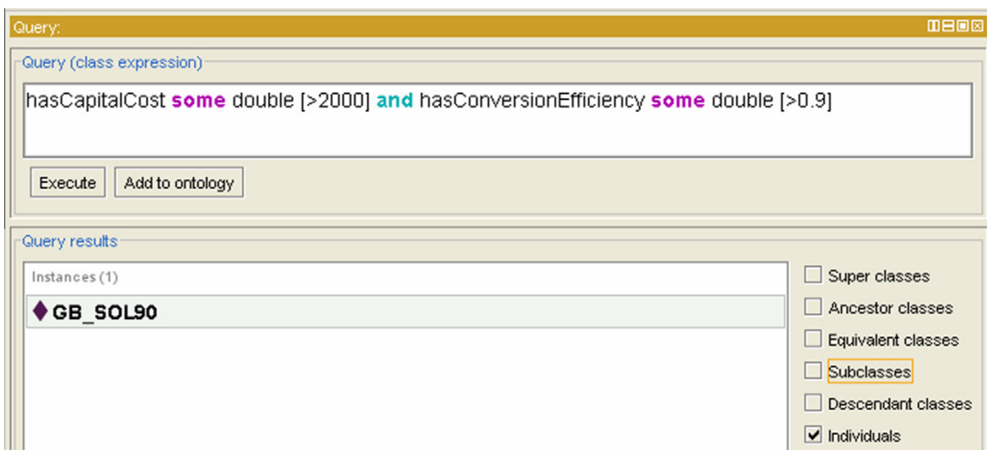

Fig. 6. The selection of a photovoltaic system with cost and energy conversion efficiency constraints.

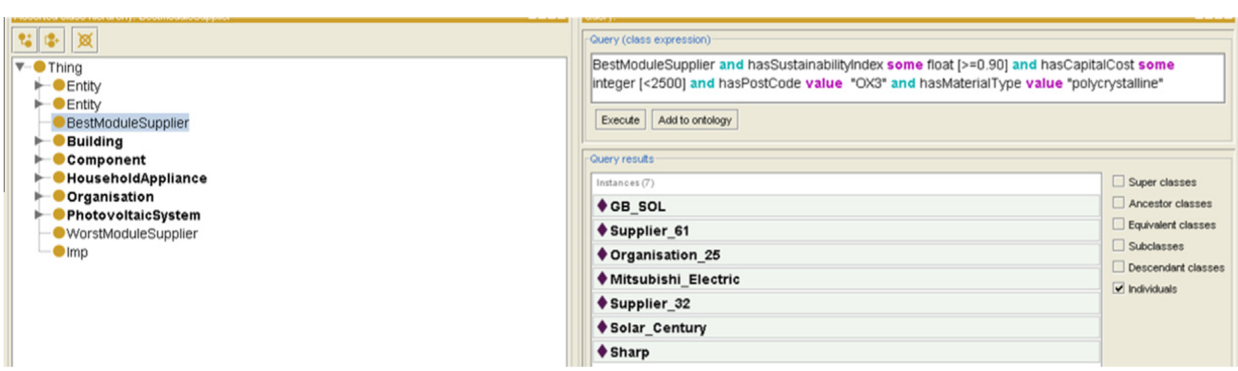

Fig. 7. The selection of the photovoltaic system best supplier.

purchase the photovoltaic system. This is modeled in DL as hasPostCode value "OX3". This is added to the client's second constraint. The execution of this query outputs best suppliers located in the same region where the client resides. Lastly, the client's small roof means a highly efficient photovoltaic system module will be appropriate as high efficiency is inversely proportional to the module size. Also the high module efficiency is proportional to the photovoltaic system module material types. For instance, polycrystalline, monocrystalline and amorphous modules are three different module materials of decreasing module efficiency. To address this constraint, the material type is set to a value of "polycrystalline" and represented in DL as hasMaterialType value "polycrystalline". This is added to the first three queries and when executed the results are as in Fig. 7.

The above queries are indicative and many more have been developed and included in the photovoltaic system ontology knowledge base. Some could be used in determining the dimension of a photovoltaic system module and even the location of a given supplier or installer. This exploits the richness of the ontology to include concepts that capture the information about the dimensions and location of suppliers and installers of photovoltaic systems. The achievement of these three results (Figs. 5–7) are principally based on the fact that inferencing in ontologies relies on inferred facts which is very complex to be expressed in conventional databases. One of the fundamental differences between conventional database systems and OWL knowledge base systems is the fact that the former is based on closed world reasoning while the latter is founded on open world reasoning [51]. In closed world reasoning, "negation is considered as a failure" i.e. "anything that cannot be found is false". On the other hand, in open world reasoning, "negation is considered as a contradiction", i.e. "anything might be true unless it is proven false". This is just one of the differences that exist between conventional database systems and ontology knowledge base systems that underpin the way reasoning can be performed and the differences in query outputs. There are a plethora of these differences and many advantages of an ontological knowledge base for Semantic Web applications [6] not to be reviewed in this article. Although these advantages can be exploited for use in building projects, research into how the results can be represented in user-friendly interfaces for practitioners who lack computer science skills are still very limited. Easy ontology browsers that can be used for manipulating ontologies are still lacking and the few that exist such as OWLSight are still very limited in strength [52]. Hence, there is still a lot of work needed to develop Semantic Web browsers with user-friendly interfaces for easy ontology manipulation and this is beyond the scope of the work presented in this paper. The ensuing section will be devoted to validating the photovoltaic system ontology examined in the preceding sections.

4.2.2. Validation of the prototype

A major recommendation in most methodologies is the validation of any ontology knowledge base. In general the validation of an ontology requires firstly that the ontology is semantically correct and secondly that the ontology is free from anomalies. The third which is often optional is to perform a probe test to reconfirm that the ontology is free of anomalies. Although the use of a probe test is not a necessary requirement for validation it is often used as a confirmatory or as a double check in ensuring that the knowledge model is free from anomalies.

Given that the ontology has been semantically validated in Section 4.1.3, this section will focus on the checking anomalies. With respect to checking anomalies, the photovoltaic system ontology was checked against subsumption, instantiation and consistencies [2]. Currently, there exist two major methods of performing anomalies checking of an ontology [51], i.e. manually and automatically. Automatic checking is achieved through the use of DL reasoners. We therefore adopted the latter method of consistency checking of the photovoltaic system ontology. This choice was guided by the availability of the reasoner FaCT++ plug-in incorporated in protégé 4.0.2 used in this work. In protégé 4.0.2, the task of checking anomalies in the photovoltaic system ontology was achieved through the use of FaCT++. In protégé 4.0.2 the manually constructed taxonomy is called *asserted hierarchy* while the computed hierarchy is called the *inferred hierarchy*. Evidence of automatic computation of an ontology using FaCT++ is revealed through the appearance of "Nothing" in the colour red in the inferred hierarchy pane of protégé 4.0.2 [50]. Fig. 6 shows the asserted hierarchy and the inferred hierarchy before and after automatic computation by FaCT++. There is no difference between the taxonomy in the asserted and inferred hierarchy except the appearance of the word "Nothing". The FaCT++ operates internally based on DL reasoning to produce the results in Fig. 8.

The ontology is said to be complete, if it is free of anomalies and has been semantically validated. However, in practice after an ontology has been developed and anomalies checked and semantically validated, temporal or permanent classes are introduced into the ontology to test whether the ontology was correctly built

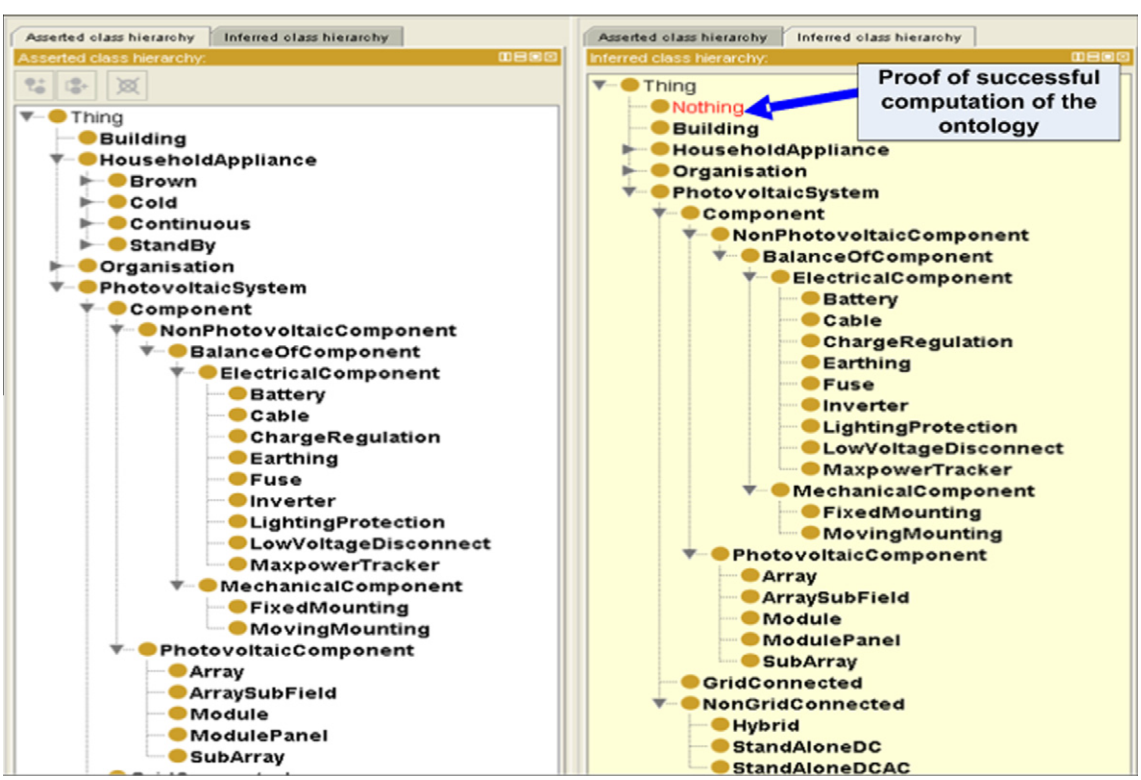

Fig. 8. Consistency checking of the photovoltaic system ontology.

[50,51]. The introduced concepts are often called probe classes. A probe test [50] aims to test an ontology design by deliberately introducing predictable faults to the ontology and then observe its effects on the model when used. The main goal of a probe test is to ensure that, disjoint axioms have been appropriately defined. Appropriateness in the definition of axioms means specifying axioms between classes where they are necessarily required and not specifying them where they are not required. This is because, in OWL open world reasoning, OWL classes "overlap" unless they have been explicitly stated to be disjoint from each other [50]. If certain classes are not made disjoint from each other, then unexpected results can arise. Accordingly, if certain classes have been incorrectly made disjoint from each other, then this can also give rise to unexpected results.

Based on the literature review on photovoltaic system, it emerged that some concepts should be made disjoint with respect others while some should not. This makes the probe test for testing disjoint axioms imperative. As a first example, a concept such as "BalanceOfComponent" with sub-classes as "mechanical component" and "electrical component" are clearly disjoint. These sub-classes are disjoint because both cannot have a common instance, or even common sub-classes. From Fig. 3, a "FixedMounting" which is "mechanical component" cannot be a "battery" which is an "electrical component". Based on OWL open world reasoning, this needs to be defined otherwise, a DL reasoner will be unable to detect that an instance of a "battery" cannot be an instance of a "FixedMounting".

To test if the disjoint axiom was defined in the "BalanceOfComponent" concept, a probe class called "ProbeInconsistencyBalanceOfComponent" was introduced as a sub-class of the "mechanical component" and also as a sub-class of the "electrical component". Next an anomaly test was conducted using Fact++ as explained above. There was an inconsistency error message for "ProbeInconsistencyBalanceOfComponent" in the test result and this probe was then removed. If the inconsistency error message had not occurred, then the disjoint axiom would have been specified between the "mechanical" and "electrical" components and the probe test re-examined until the test result is free of errors. Once the test result is free of errors, then the probe class is removed.

The second example of disjoint axiom verifies whether the disjoint axiom has been defined where it was not supposed to be defined. As earlier mentioned in Section 4.1.2, a non-grid-connected system can be a stand-alone DC, a stand-alone DC–AC, or a hybrid of both. The main components of stand-alone DC are a battery, charge controller and a PV-array. The main components of a stand-alone DC–AC are a battery, charge controller and DC–AC inverter. The components of a hybrid system are a battery, charge controller, DC–AC inverter, system controller, battery controller and generator. This means that in modelling the classes stand-alone DC; stand-alone DC–AC and hybrid as different types of ontology classes they should not be made disjoint. This is because you can have a battery that is an instance of stand-alone DC, stand-alone DC–AC and hybrid systems. In order to test whether the disjoint axiom has not been imposed between the stand-alone DC, stand-alone DC–AC and hybrid systems, the ProbeInconsistencyBalanceOfComponent" is introduced as sub-class of these classes and the reasoner FaCT++ was executed. There were no error messages signifying that the disjoint axiom has not been specified. The ProbeInconsistencyBalanceOfComponent" class is then removed. Suppose there was an error message, then the disjoint axiom might have been defined between the classes and needs to be taken off and the reasoner FaCT++ executed until no errors detected. The ProbeInconsistencyBalanceOfComponent" can now be removed. Practically, this means that during the population of the stand-alone DC; stand-alone DC–AC and hybrid systems with instances, no error message will emerge if the same instances created in two or more classes have not been specifically made disjoint at development time.

5. Conclusion and further research

In this paper, we have investigated the application of the Semantic Web technologies to the sustainable building technology domain with focus on the photovoltaic system. Despite being an initial exploratory study, this work is an important step towards exploring in greater detail the possibilities of implementing the Semantic Web technologies in the sustainable building technology domain. The growing importance for mitigating environmental impacts from buildings and the need for more energy efficient or environmental friendly buildings create the need for the incorporation of more sustainable building technologies into buildings. This in turn imposes the need for an effective way to manage information being generated from emerging sustainable building technologies. Based on the current trend of studies about the Semantic Web technologies, ontology engineering forms the basis of the success of the Semantic Web technologies. Furthermore, representing domain knowledge using ontologies allow for the additional incorporation of knowledge and possible integration with other programs. We have therefore described the photovoltaic system ontology developed in protégé-OWL, and presented scenarios demonstrating the strengths of querying using the DL in a Semantic Web environment. The OWL photovoltaic system ontology benefited from existing ontologies that were extended, enriched and re-used. The practice of re-using existing ontologies is a key advantage in terms of interoperability with respect to the Semantic Web vision. As the Semantic Web vision matures, further work will be required to develop Semantic Web-based browsers with user friendly interfaces to allow individuals and practitioners to be able to undertake queries and searches without the need to understand DL query constructs.

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