Knowledge modelling of emerging technologies for sustainable building developmentFonbeyin Henry Abanda (2011)

Note if anything has been removed from thesis: Fig. 2.3, p. 43; fig. 2.4, p. 44; fig. 2.5, p. 45; fig. 6.11, p. 164

KNOWLEDGE MODELLING OF EMERGING TECHNOLOGIES FOR SUSTAINABLE BUILDING DEVELOPMENT

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ABSTRACT

In the quest for improved performance of buildings and mitigation of climate change, governments are encouraging the use of innovative sustainable building technologies. Consequently, there is now a large amount of information and knowledge on sustainable building technologies over the web. However, internet searches often overwhelm practitioners with millions of pages that they browse to identify suitable innovations to use on their projects. It has been widely acknowledged that the solution to this problem is the use of a machine-understandable language with rich semantics - the semantic web technology.

This research investigates the extent to which semantic web technologies can be exploited to represent knowledge about sustainable building technologies, and to facilitate system decision-making in recommending appropriate choices for use in different situations. To achieve this aim, an exploratory study on sustainable building and semantic web technologies was conducted. This led to the use of two most popular knowledge engineering methodologies - the CommonKADS and "Ontology Development 101" in modelling knowledge about sustainable building technology and PV-system domains. A prototype system - ***P***hoto***V***oltaic ***T***echnology ***ON***tology ***S***ystem (PV-TONS) - that employed sustainable building technology and PV-system domain knowledge models was developed and validated with a case study.

While the sustainable building technology ontology and PV-TONS can both be used as generic knowledge models, PV-TONS is extended to include applications for the design and selection of PV-systems and components. Although its focus was on PV-systems, the application of semantic web technologies can be extended to cover other areas of sustainable building technologies. The major challenges encountered in this study are two-fold. First, many semantic web technologies are still under development and very unstable, thus hindering their full exploitation. Second, the lack of learning resources in this field steepen the learning curve and is a potential set-back in using semantic web technologies.

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Finally, I owe special and everlasting thanks, praise and adoration to the Almighty God for his immense love, provision, protection against all odds and for having guided me during this research period.

DEDICATION

To my wife, Ntembo Nancy Mbikinyi Abanda and our expected little one, for their love, endurance and support whilst I was away pursuing the PhD programme.

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LIST OF ABBREVIATIONS

3D	3-dimensional
AC	Alternating Current
aecXML	Architectural, Engineering and Construction XML
AHP	Analytic Hierarchy Process
API	Application Programming Interface
bcXMLBuilding	Building and Construction eXtensible Mark-up Language
BIM	Building Information Modelling
BRE	Building Research Establishment
BREEAM	BRE Environment Assessment Method
CH_4	Methane
CO_2	Carbon Dioxide
CommonKADS	Common Knowledge Acquisition and Documentation Structuring
CSS	Cascading Style Sheets
DBMS	Database Management System
DC	Direct Current
DC-AC	Direct Current/Alternating Current
DL	Description Logics
EU	European Union
FaCT	Fast Classification of Terminologies
GUI	Graphical User Interface
HTML	Hypertext Markup Language
IBM	International Business Machines
ifcXML	Industry Foundation Classes XML
J2SE	Java 2 Platform, Standard Edition
JDBC	Java Database Connectivity
JSP	JavaServer Pages
KAON	KArlsruhe ONtology
MOKA	Methodology for Knowledge-Based Engineering Applications
N_2O	Nitrous Oxide
nRQL	New Racer Query Language
OWL	Web Ontology Language
PC	Personnal Computer

PV- system	Photovoltaic system
PV-TONS	**P**hoto**V**oltaic **T**echnology **ON**tology **S**ystem
RDF	Resource Description Framework
RDFS	Resource Description Framework Schema
RDMS	Relational Database Management System
RDQL	RDF Data Query Language
SQL	Structured Query Language
SQWRL	Semantic Query-Enhanced Web Rule Language
SWRL	Semantic Web Rule Language
TOGA	Top-down Object-based Goal-oriented Approach
TOVE	**TO**ronto **V**irtual **E**nterprise project
UK	United Kingdom
UML	Unified Modelling Language
URI	Uniform Resource Identifier
US	United States
WebODE	Web Ontology Design Environment
WWW	World Wide Web
XHTML:	eXtensible HyperText Markup Language
XML	eXtensible Markup Language
XMLS	XML Schema
XSL	eXtensible Stylesheet Language

SYMBOLS

$=$	is equal to
$>$	is greater than
$<$	is less than
$^\circ$	the degree sign used in separating a collection construction clause and a standard SWRL pattern specification.
$\rightarrow$	implies
$/$	divide
Σ	the sum of the terms indicated (sigma)
$I_{S,1}$	environmental sustainability index
$I_{S,2}$	social sustainability index
$I_{S,3}$	economic sustainability index
$I_{S,T}$	technical sustainability index
$I_{S,P}$	physical sustainability index
SI	total sustainability index
$I^{+}_{N,ij}$	normalised indicator *i* of type "more is better" for group indicators *j*
$I^{-}_{N,ij}$	normalised indicator *i* of type "less is better" for group of indicators *j*.

1. INTRODUCTION

1.1 General

The environmental impacts of construction are now well documented (Weight and Rawlinson 2007; Levin 2008). Consequently, many environmental agencies and governments are now recommending change in practices, use of advanced and innovative technologies as strategies for the mitigation of the environmental impacts from construction projects. These agencies and governments are supporting these recommendations with the provision of grants and funding for projects that implement innovative technologies such as sustainable building technologies leading to the mitigation of environmental impacts. Despite this support and the benefits of incorporating sustainable building technologies in construction projects, their uptake has been very low (Cooke *et al.* 2007; Foxon and Pearson 2008). Some studies have revealed that although there exists too much information in different media about sustainable building technologies, the lack of knowledge about the same is still very common among construction professionals and end-users (Powell and Craighill 2001; Taylor and Wilkie 2008; Hall 2006). This has been regarded as one of the greatest barriers to the uptake of sustainable building technologies as one of the major strategies in the mitigation of environmental impacts from construction projects. Therefore, there is a need for better ways of managing construction information for better exploitation by construction professionals. This study investigates the use of advanced information technology, the semantic web technology, in the acquisition of knowledge about the domain of sustainable building technology. The semantic web technology is an emerging technology and the next generation of the web technology or "a new form of web content that is meaningful to computers and will unleash a revolution of new possibilities" (Berners-Lee *et al.*, 2001).

1.2 Background

The argument that atmospheric greenhouse gases are the major contributors of high temperatures on earth is now widespread (Stern 2006; Stolarski *et al.* 2010). The most abundant greenhouse gases are water vapour, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone and chlorofluorocarbons. In order to maintain the Earth's temperature constant, it is imperative to maintain the balance of greenhouse gases in the atmosphere. This can be achieved if an inventory of the sources of the different greenhouse gases are known and strategies put in place to control the flux into the atmosphere (Stern, 2006).

The two main sources of greenhouse gases are natural and man-made. Natural sources include water vapour in the atmosphere; the release of CO_2 from volcanic activities and the breathing of people and animals, CH_4 that comes from digestion of food by cattle, the release of N_2O from the death and rot of plants and the natural occurrence of ozone. The man-made greenhouse gas sources are the burning of fossil fuels to heat homes, to run cars and operate machineries for the production of electricity, construction activities and the manufacture of products for different purposes. In general man-made greenhouse gas emissions are due to human activities from different sectors of life.

By the nature of the type of activities and the machineries involved, construction is one of the sectors that contribute significantly to the emission of greenhouse gases. According to the World Resources Institute's estimates, buildings emit about 15% of global greenhouse gases (Levin 2008; de la Rue du Can and Price 2008). In the UK, energy use in homes accounts for around 25% CO_2 emission (CLG, 2006). Furthermore, the impact of construction waste also contributes to affecting the climate. Construction activities will always produce waste and it is perhaps as a result of this that 40% of all landfill waste in UK is building waste (Weight and Rawlinson, 2007). Besides, construction waste can cause negative impacts on the environment, including air and/or water pollution which mostly occurs from waste transportation, emissions from vehicles/machinery, noise, release of contaminants and the composition of wastes in landfills (Yahya and Boussabaine, 2006). In tackling the climate change impacts, UK organizations have placed more importance and interest in sustainable construction practices especially in building development projects. Furthermore, pressure from various agencies within the UK construction industry to incorporate sustainable building technologies into its building projects has been increasing. This is an additional burden to the construction industry as it is already heavily laden with other problems such as project and knowledge management of projects (Dainty *et al.* 2005; Egan 1998); poor construction time, poor cost and quality performance (Egan 1998; Latham 1994; Kagioglou *et al.* 2001) and the fragmented nature of the industry (Egan 1998; Latham

1994; Kagioglou *et al.* 2001). Despite the government's constant support, motivation and recommendations for the uptake of sustainable building technologies, many construction companies have reacted with mixed feelings and have expressed reluctance to engage with the request (Pitt *et al.* 2009; Taylor and Wilkie 2008; Egan 1998; Dewick and Miozzo 2002; Sayce *et al.* 2007). Dewick and Miozzo (2002) argue that institutional barriers (such as corporate governance structure, profit motivation and the extent of stakeholder ownership) and lack of information flows are some of the major reasons that contribute to the reluctance to the uptake of these technologies. Taylor and Wilkie (2008), Sayce *et al.* (2007) and Egan (1998) argue that the lack of collaboration between construction project partners which inhibits information flows contributes to the reluctance for the uptake of sustainable building technologies. Pitt *et al.* (2009) argues that the lack of fiscal incentives and regulations inhibits the uptake of sustainable building construction as a whole.

Although an overview of the different barriers for the uptake of sustainable building technologies into building construction projects will be made later in section 2.3.7, a critical analysis will focus on information-related barriers. This is because; information-related barriers are key to the establishment of the rationale of this study. Furthermore, it is not feasible to provide a detailed analysis of all the barriers for the uptake of sustainable building technologies in this study. In the ensuing paragraph, the challenges associated with the sheer size of information being generated by the sustainable building technologies and the most popular and widely used media, the internet, are examined.

Firstly, the advent of sustainable building technologies is generating too much information making it difficult for construction professionals to make informed decisions about different technologies to be incorporated in their projects. Hence, the implementation of better knowledge management techniques for knowledge modelling, storing, understanding and sharing information about the domain of sustainable building technologies is necessary to facilitate decision-making in building projects. However, there is still very limited understanding of the best ways to foster the creation of knowledge, let alone on how to capture it, and even less on how to ensure that knowledge is readily available to individuals, project teams and companies (Shelbourn *et al.*, 2006).

Secondly, another challenge is inherent in the use of the current web, the best and the most widely used medium in publishing information about different domains and sustainable building technologies in particular. The current web has made a huge amount of information available to end-users and has been a success story in terms of growth rate of human users. This success and exponential growth of information have rendered the web increasingly difficult to find, to access, to present, and to maintain information of use to a wide variety of users (Fensel *et al.* 2005; Lacy 2005; Antonio and van Harmelen 2004). This is one of the major reasons why its exploitation has been very slow despite sustainable building technology information being abundantly available on the web. It is therefore imperative to explore other media for management of knowledge about sustainable building technologies so as to enhance their uptake by professionals in building development projects. The semantic web technology which is based on ontology knowledge modelling principles has emerged with a new vision to overcome the current shortcomings of the current web and possesses so many potential opportunities. These opportunities can be exploited in providing decision-support tools to practitioners in making appropriate choices of sustainable building technologies for use in various applications. The semantic web will be examined in Chapter 3. The rationale, aim and objectives of this study will be examined in the ensuing sections.

1.3 Rationale

Globally, the construction industry contributes significantly to the economy of most countries. In the UK, for example, it accounts for 10% gross domestic product (GDP) (DTI, 2007). Despite being an important sector to most countries including the UK, the sector is one of the largest resource consumer and polluter of the environment. Some of the major pollutants are greenhouse gases with CO_2 being the most abundant. For example, in the UK, energy consumption in buildings currently accounts for around 47% of the nation's CO_2 emission (Edwards, 2010) while the built environment in general is responsible for over 50% of the UK energy consumption (Mulholland *et al.*, 2006). The energy use in the UK housing sector accounts for over 27% of UK CO_2 emissions (DEFRA, 2007). The consumption of natural resources and emission of CO_2 and waste have been undoubtedly proven to have serious impacts on the environment including the human well-being (Holtzhausen 2007; Horvath 2004). Estimates by Dunster *et al.* (2009) reveal that a typical four-person UK household that is responsible for 12 tonnes CO_2 per year over three generations will be directly responsible for the suffering of people in a climate change hot spot. Climate change hot spots are regions or areas that may be at relatively high risk of adverse impacts from one or more natural hazards as a result of climate change (Giorgi, 2006).

Therefore, it is imperative for most governments including the UK's to implement climate change mitigation strategies to avoid or lessen adverse consequences on the environment and the society at large. The response from the UK government towards the implementation of mitigation strategies has been positive. One such response has been the government's involvement in many international and national commitments. The UK is committed to international binding initiatives aimed at reducing its greenhouse gas emission levels. An example is the Kyoto protocol, which legally binds the UK to reduce its CO_2 emissions by at least 12.5% below the 1990 levels over the period 2008-2012 (Hickman and Banister, 2007). This is however, a minimum requirement and a guide only as the UK government has internally set its own targets that can enable achievement of even higher targets. For example, the UK government has set its CO_2 emission reduction target to 80% by 2050 compared to the 1990 levels (DEFRA, 2008). Intermediate targets of a 20% reduction by 2010 and 30% by 2020 have also been set (Hickman and Banister, 2007). These commitments will require carbon reductions to be made by all sectors including the building sector (Stern, 2006). Consequently, the government has highlighted the building sector as a key sector, as it is the sector with a greater opportunity to achieve significant carbon reductions. This has been backed by the government policies to achieve or maximise this opportunity by introducing some stringent standards.

Recent UK's government report reveals that construction professionals are not only required to comply with stringent standards but that the commitment to the reduction of carbon and other greenhouse gas emissions is a legal obligation (BIS Construction Innovation Growth Team Final Report, 2010). The two most important UK building standards are the Code of Sustainable Homes (CLG, 2007) and the Building Regulations (Planning Portal, 2010). The Code of Sustainable Homes is a national standard for the sustainable design and construction of new homes. The code measures the environmental performance of new homes vis-à-vis the following environmental impact categories: energy/CO_2, water, materials, surface water run-off, waste, pollution, health and well-being, management and ecology. One of the main aims of the code is to reduce carbon emissions and create homes that are more sustainable. As part of this goal, the government has set out in its Building a Greener Future Policy Statement, that new homes will be net zero carbon from 2016 (CLG, 2007). In order to achieve this target, energy efficiency standards for new homes are to be improved by 25% in 2010 and 44% in 2013 relative to current 2006 standards (CLG, 2007). The Building Regulations apply to building work in England and Wales and set standards for the design and construction of buildings to ensure the safety and health of people in buildings (Planning Portal, 2010). The Building Regulations also contain requirements to ensure that fuel and power is conserved and facilities are provided for people, including those with disabilities, to access and move around inside buildings (Planning Portal, 2010). Although most of the requirements in these standards are mandatory, there are no specified mandatory technologies that can be used to achieve the required targets. This means that while clients may be interested in choosing technologies that improve the performance of their buildings they also need ways of determining the different technologies and how the technologies can be used in the achievement of the requirements in standards such as the Code of Sustainable Homes and the Building Regulations.

Society and governments around the world are therefore 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 current web to facilitate accessibility and use. The emergence of the World Wide Web (WWW) has brought exciting new possibilities in information access and electronic business. The WWW has grown to be the largest distributed repository of information ever created. Estimates reveal that the web currently contains about 3 billion static documents and being accessed by over 500 million users from around the world (Bui *et al.*, 2007). An estimate by the United Nations agency put the number of internet users to exceed 2 billion (nearly a third of the world's population) in 2010 (BBC, 2010). Web content consists largely of distributed hypertext and hypermedia, accessible via keyword-based search and link navigation.

Although the attraction of the web lies in its simplicity and ease of accessibility (Fensel *et al.*, 2005), the sheer 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 (Fensel *et al.* 2005; Antonio and van Harmelen 2004; Berners-Lee *et al.* 2001; Gruber 1993). 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 (Fensel *et al.* 2005; Antonio and van Harmelen 2004; Berners-Lee *et al.* 2001; Gruber 1993). Key to this, is the use of a common language or an ontology (Gruber, 1993) for representing knowledge from different sources to facilitate decision-making. According to Gruber (1993), *"an ontology is an explicit specification of a conceptualisation"*.

According to the WWW Consortium (W3C, 2010), 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 (Horrocks, 2008). However, considerable progress is being made in the infrastructure required to support the semantic web, particularly in the development of languages and tools for content annotation and design and deployment of ontologies. No wonder there has been an upsurge in research in the investigation of the use of semantic web technologies in the development of applications in different domains. Some notable examples of research that investigates the application of the semantic web are in the fields of publishing, judiciary, bioinformatics, finance, and energy (Antonio and van Harmelen 2004; Warren *et al.* 2006). Furthermore, some studies of semantic web applications to the construction domain are also available (El-Diraby *et al.* 2005; Rees 2006; Ruikar *et al.* 2007). However, knowledge of how these technologies can be applied to the sustainable building technology domain is still very limited and overshadowed by the penchant among professionals to stick to old ways of doing things.

1.4 Aim and objectives

The aim of this study is to investigate the extent to which semantic web technologies can be used in developing a decision-support tool for practitioners in making appropriate sustainable building technologies choices for their building projects.

The objectives are:

- To identify, and critically assess the role of sustainable building technologies in the context of sustainability;
- To identify gaps in current web technology in managing sustainable building technology information and exploration of how semantic web technologies can be used in bridging the gaps;
- To elicit, model, and represent sustainable building technology knowledge using semantic web techniques;
- To develop and evaluate a prototype decision-support tool for sustainable building technologies selection in order to demonstrate the potential of semantic web technologies.

1.5 Summary of the research methodology

This section outlines a summary of the research approach used in this study. The study deals with two different emerging domains - the semantic web technology and the sustainable building technology. The relationship between the two domains is that the semantic web technology is applied on the sustainable building technology domain. Considering that the semantic web and the sustainable building technologies are emerging domains and based on the different research methodologies reviewed, an exploratory qualitative approach was deemed appropriate and adopted in this study (Bryman 2001; Bernard 2000). Also, a case study was employed to support the findings of the exploratory study. Although a detailed review of an exploratory qualitative research is outside the scope of this thesis, it is briefly described in section 1.5.2 to provide an understanding of the underlying philosophy of its application. To offer clarity on the summary of the methodology, it is important to state the problem domains considered in this research.

1.5.1 Identification of the problem domain

After reviewing the sustainable building and semantic web technology domains it was noted that both domains involve other domains and problem areas and that it was not feasible to tackle all of them within the time frame available for this research. With regards to the purpose of this study four key areas constitute the problem areas of this research.

Firstly, to provide an overview of the problem area, the sustainable building technology area was identified as a representative problem area. In this study, the key issues covered in the sustainable building technology domain include the different types of sustainable building technologies, the advantages and disadvantages, the barriers to their uptake in building construction projects, and a generic ontology knowledge model of the sustainable building technology domain. However, to demonstrate key applications of semantic web technologies, the sustainable building technology domain was further scoped down to the PV-system domain. Not only is the PV-system increasingly becoming popular in the UK, its significant reduction in greenhouse gas emissions required to meet the climate change targets makes it an appropriate choice. Its negligible environmental impacts and highly energy-saving advantages over other renewable energy technologies further justifies its choice as a suitable area to focus on. Although, at the moment the cost of PV-systems is still more expensive than most renewable energy technologies (Evans *et al.*, 2009), other literature suggests that with technological improvements and an increase in production rates, the cost set-back can easily be overcome (Varun *et al.*, 2009).

Secondly, given that sustainable building technologies can be used in different sectors (e.g. PV-system can be used in electronics and the construction industry), it was necessary to focus the study on a particular sector. The building industry was the logical choice because: it is the sector that consumes the highest natural resources while at the same time the sector that has the highest cost and carbon-savings potential. However, as the building sector is part of the construction industry, some sections in this thesis have been examined from a more holistic approach by reviewing the construction industry before highlighting some key facts about the building sector. This was however a challenge to avoid, as the construction industry is so blurred as there is no clear demarcation between its constituent sectors (Harvey and Ashworth, 1993).

Thirdly, based on the applications of semantic web in this study, it was necessary to scope down the particular types of applications. Three types were considered. The first application which constitutes a lightweight ontology about the domain of sustainable building technology provided a holistic overview of the ontology knowledge based in this study. Lightweight ontologies are taxonomy of concepts describing a domain and often related by the "is-a" relationship (Gómez-Pérez *et al.*, 2004). The second application focused on the semantic web selection decision-support system of the PV-systems. The last application focused on the design of the PV-system using semantic web techniques. Given that the last two applications require constraints to enable the application functional, the underlying ontology was a heavyweight. Heavyweight ontologies model a domain in a deeper way and provide more restrictions on domain semantics (Gómez-Pérez *et al.*, 2004). The focus of these applications was on back-ends rather than front-ends and so no easy to use or user-friendly interface was built for use by non-ontology engineers. This choice was justified by the fact that the front-ends or interfaces of semantic web applications vary and are often designed to meet the various requirements of different end-users. As part of future research, an investigation towards the development of interfaces that will employ the back-ends will be conducted.

Fourthly, based on the fact that only the back-end of the prototype will be developed, the targeted audience are those playing advisory roles in the use of sustainable building technologies. Although any end-user with minimal computer skills can query the prototype, main audiences include sustainable building technology consultants, developers and home owners. To facilitate, easy acquisition of information and knowledge from the prototype by the audiences with minimal computer science skills, the Protégé-OWL related plug-ins (e.g. Semantic Web Rule Language Tab

(SWRLTab)) has been incorporated into the prototype. It is easier to learn and run rules and queries in SWRLTab than to query the main Protégé-OWL editor.

1.5.2 Brief description of the research methodology

Exploratory research provides an insight into and comprehension of an issue or situation. The outcome of an exploratory research is the establishment of primary findings that will dictate the path of subsequent procedures or activities of the study. Based on the findings or claims, evidence should be formulated to support the findings or claims. In such circumstances, evidence is taken to mean a convincing argument in support of a claim or hypothesis, a justification from data analysis, and a *proof-by-demonstration.* In computer science prototypes are often used as a proof-by-demonstration piece of evidence in support of a claim (Pan, 2006). In the implementation of the research approach, the sustainable building technology domain was first explored. A variety of techniques including desk study and informal discussions were used to capture knowledge about the sustainable building technology domain. This exploratory study on the domain of sustainable building technology led to the establishment of the state-of-the-art of sustainable building technology, identification of the barriers for the uptake of sustainable building technologies, and the establishment of why there is need for ways of efficiently managing sustainable building technology knowledge. This provided an insight into the nature of knowledge to be investigated about the semantic web technology. Furthermore, in consideration of the available resources and the large scale of the sustainable building technology domain, it was decided that it would be more informative from a research perspective to focus on a specific sustainable building technology. It is for this reason that the PV-system domain was chosen. In addition to the rich environmental values of the PV-systems, they are currently generating a lot of interest in the building area with high public visibility.

After the exploration of sustainable building technologies, semantic web technology was explored. Like in the sustainable building technology domain, the state-of-the-art of semantic web technologies was established. This exploration of semantic web technology was undertaken through literature review and participation in training courses, conferences and writing of papers for journal consideration. In total, ten peer-reviewed conference papers, one book chapter, one peer-reviewed research project were published. Furthermore, five journal submissions were made. Out of these, four have already been accepted for publication. The reviewers' comments of one of the submissions are still pending. Feedback from these publications, submission and informal discussions with other researchers during conferences contributed significantly to validating some of the results that emerged from exploring the sustainable building and semantic web technology domains.

Two major outcomes of exploring semantic web domain are the identification of specific technologies that can be used in modelling sustainable building technology domain and the identification of the components of the semantic web technology that enhances the current web technology. For instance, representing sustainable building technology knowledge using the web ontology language (OWL) is an outcome based on the review of different ontology languages. Based on other outcomes such as the availability of rich and high expressive language power for modelling sustainable building technology knowledge, availability of efficient search techniques and the availability of rule languages that can easily be used in managing sustainable building technology knowledge, a prototype was developed to verify and prove these concepts. To provide a holistic view of semantic web technology, a generic knowledge model on sustainable building technology was developed and the prototype system developed was focused on PV-system technology. Proof by using prototypes is one of the ways of justifying claims or findings in an exploratory study. The link between the exploratory study and a prototype is represented in Figure 1.1.

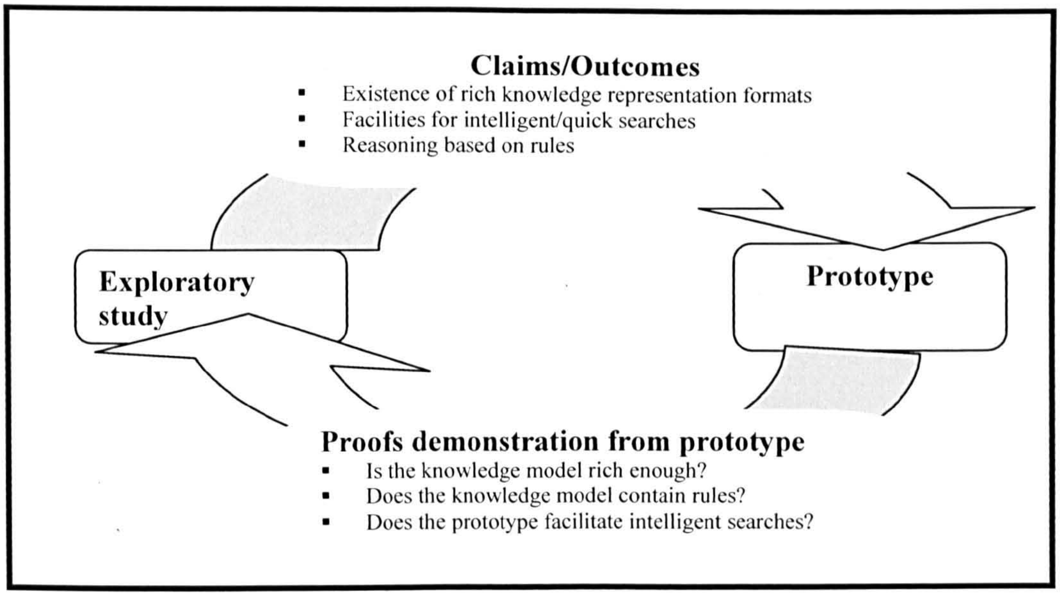

Figure 1.1. Relationship between exploratory and prototyping research paradigms

Having developed the prototype system, it is necessary to evaluate the system with real data instead of simulated data (Sommerville, 2007). In this regard, a real-world case study was used to validate the prototype system. The development of a prototype validated through the use of real-world case study to demonstrate the capabilities of the semantic web technology led to the achievement of the aim of this study.

1.6 The main achievements

The work undertaken in this study was motivated by the need for an information technology methodology for the development of tools for the support of knowledge discovery processes on sustainable building technologies that can be used in making informed decisions. Furthermore, it was established through literature review that the most popular and widely used technique of information dissemination, i.e. the current web technology, has been very limited in disseminating knowledge about different domains. This partly constituted the rationale for the investigation of better ways of knowledge representation techniques such as the semantic web technology that can be used in the domain of sustainable building technology. However, in order to exploit the potentials of the semantic web technology, information about the domain of sustainable building technology had to be modelled differently from conventional methods, e.g.

ontological representations. The search for new knowledge representation tools and techniques led to the following main achievements:

- Conceptual knowledge models of the sustainable building technology domain that can be exploited for further use;
- An ontology that models knowledge about sustainable building technology suitable for use in application development;
- An ontology that models knowledge about PV-system technology suitable for use in application development;
- The establishment of a semantic web approach that enables knowledge in the sustainable building technology domain and the PV-system technology domain to be represented and interpreted by computers for decision-support purposes;
- A technique for integrating multi-criteria selection techniques with rule-based techniques in a decision-support system;
- A prototype system for PV technology decision-support (known as PV-TONS meaning "*P*hoto*V*oltaic *T*echnology *ON*tology *S*ystem") demonstrating the potentials of semantic web technology.

1.7 Organization of the thesis

The thesis consists of nine chapters. The structure and order of writing of the chapters is presented in Figure 1.2 and the content of each chapter is briefly described.

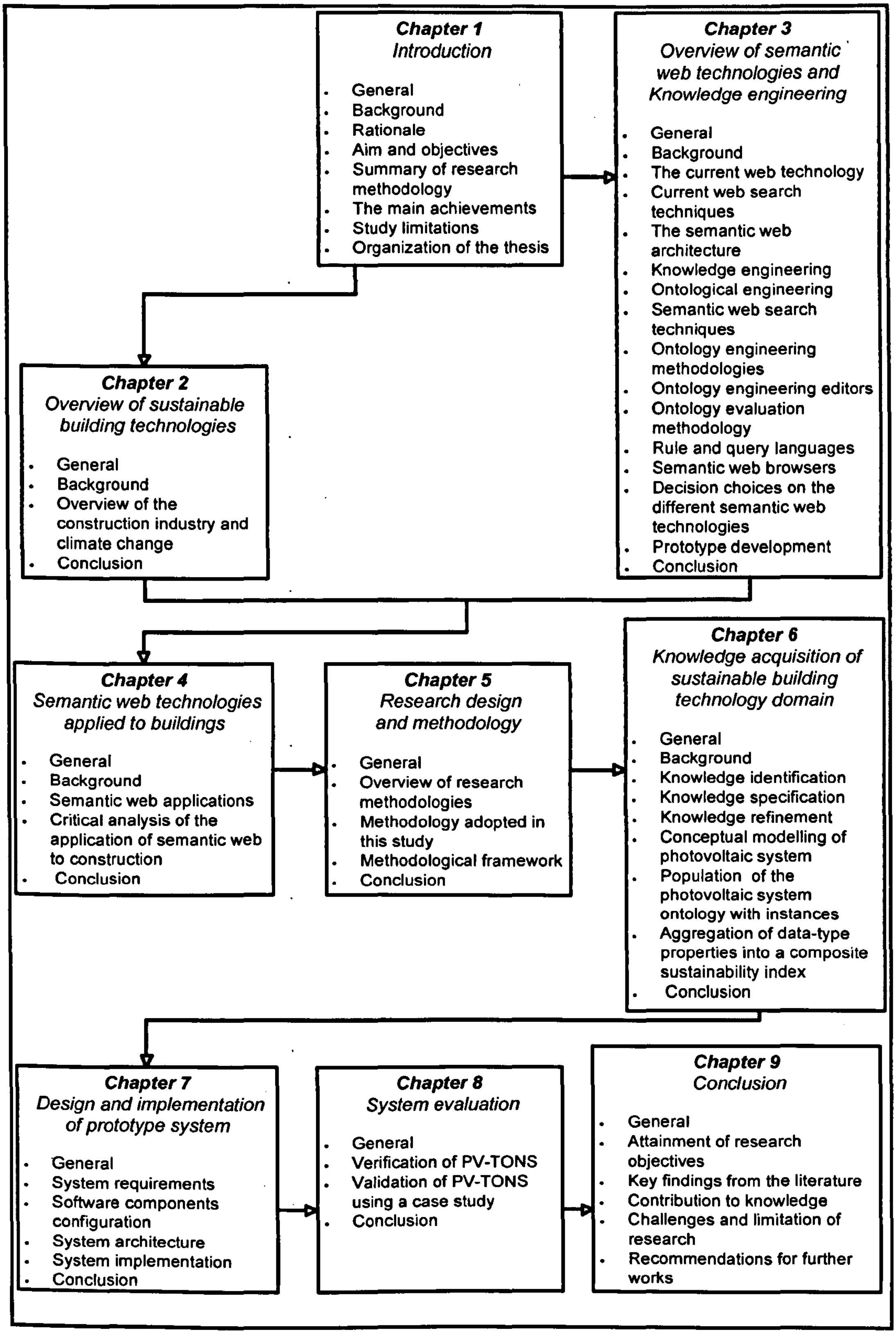

Figure 1.2. Structure of the thesis

The first chapter presents the general background to the study. It highlights the main issues associated with construction activities in relation to environmental impacts. Furthermore, the chapter examines the role of sustainable building technologies in the drive for sustainability including challenges associated with their incorporation into building development projects. The chapter further argues the role knowledge about sustainable building technologies could play in enhancing the integration of these technologies into building developments. A highlight of challenges using current knowledge technologies and media such as the current web in managing sustainable building technology is mentioned. To overcome these challenges, opportunities in the emerging knowledge technologies such as the semantic web that can be used in managing sustainable building technologies are discussed. In this chapter the rationale, the aim and objectives are presented. A brief summary of the main achievements and research methodology is also presented. Acting as a sign post to other chapters, a flow chart diagram depicting the thesis structure, the relationship between the chapters and order of execution is presented (see Figure 1.2).

The second chapter examines the different sustainable building technologies currently being used in the UK building industry. In particular, the chapter identified the knowledge gaps about the domain of sustainable building technology. The three main knowledge gaps identified are: the establishment of the role sustainable building technologies could play in mitigating environmental impacts within the context of sustainability, the investigation into the challenges about the uptake of sustainable building technology into building development projects, and the establishment of the need for an application of advanced information technologies which can potentially trigger the uptake of sustainable building technologies by construction professionals. The knowledge gaps led to the formulation of the rationale, aim and objectives of this study. The need for the application of advanced information technology in managing sustainable building technology knowledge led to the investigation of the use of knowledge modelling techniques, a subject of Chapter 3.

Thus, in Chapter 3, an exploratory study is undertaken to establish the emerging opportunities of the semantic web technology. Key prototyping development methodologies including software, knowledge and ontology engineering have been reviewed. The review of software engineering, knowledge engineering and ontology engineering was aimed at situating the context of this research. Based on the review of these key areas of engineering, a decision was made on whether to use one or a combination of the engineering methodologies. The choice of a combination of the above knowledge engineering methodologies led to the identification and selection of appropriate methodologies, languages and tools for building ontologies. This chapter also reviews existing ontologies for possible re-use. Upon the review of the domain of sustainable building technology and the semantic web technology domain, it was necessary to investigate previous studies on the application of semantic web technology applied to modelling knowledge about sustainable building technologies. This will be undertaken in Chapter 4.

In Chapter 4, a review of semantic web technologies applied in building construction is undertaken. This is done from three perspectives. Firstly, the application of current web techniques in facilitating knowledge acquisition in the domain of construction is reviewed. The knowledge gaps were identified and, in the second instance a review on the use of semantic web techniques applied to construction was undertaken. Like in the first perspective, the goal was to identify the knowledge gaps with a focus on the semantic web techniques. The focus was actually investigating the different types of semantic web techniques that have been applied to construction. Thirdly, a review on the different construction areas that have implemented semantic web techniques was undertaken. Some construction domains such as supply chain management, project management and construction education were identified as areas that have used semantic web techniques. A key finding from these three perspectives is that most semantic web technology applications that have been developed in the afore-mentioned areas of building construction use lightweight ontologies. It also emerged that very few lightweight ontologies have been developed in the sustainable building technology domain. Furthermore, most of the identified sematic web applications that are based on lightweight ontologies have never exceeded the prototypying stage and have hardly left from the academic benches. Thus, it was imperative to design a methodology of how to implement semantic web technologies in managing sustainable building technology knowledge, the focus of Chapter 5. Based on the review of the literature in Chapters 2 and 3 and on the understanding of the research theme, a research methodology has been designed and presented in Chapter 5. The methodology presented in this chapter will then be implemented in the subsequent three chapters, i.e. chapters 6, 7 & 8.

Chapter 6 presents the development of sustainable building technology conceptual knowledge models. It starts by first filling the gaps identified in chapter 2. Major design issues and difficulties encountered in developing the sustainable building technology conceptual knowledge models will be mentioned and how they were overcome. A Unified Modelling Language (UML) representation of the concepts, properties and their relations will be presented before an implementation of the concepts into an ontology editing, storage, reasoning environment is undertaken.

After the knowledge model has been developed in Chapter 6, it is necessary to implement it in a software environment. Thus, Chapter 7 discusses the system architecture that will be used to enhance integration and collaboration between various agents and system components for efficient decision-making. The chapter will present the different software components; demonstrate how the components have been assembled, and how it will contain sustainable building technology information. The justification of the choices of each component chosen will be stated. Furthermore, this chapter concentrates on the implementation of the systems developed in chapters 5 and 6. The chapter illustrates how the implementation has been undertaken using key semantic web technologies in the development of PV-TONS.

The prototype system developed in Chapter 7 will be evaluated in Chapter 8. Given that the first part of this study adopts an exploratory approach, it was imperative to design a chapter that will focus on justifying the claims that might have emerged from the exploratory study. Chapters 6 and 7 demonstrate how knowledge about the sustainable building technology domain can be modelled. Chapter 8 starts by evaluating the prototype system developed in Chapters 6 and 7 for technical fitness. After evaluating the prototype, the system is validated using a real-world case study. Based on the evaluation results scenarios are examined to illustrate how information can be retrieved from PV-TONS. The main aim of information retrieval from the PV-TONS will be to highlight the capabilities of a semantic web environment from an information retrieval perspective.

Chapter 9 is the concluding chapter that summarizes and synthesises the achievements of the research, the contribution to knowledge, the scope for further research, and recommendations for further study. Other than the main chapters in this thesis, additional information relevant to this research is also presented in the appendices. The appendices are as follows:

- **Appendix 7.1.** PV-TONS OWL ontology;
- **Appendix 8.1.** Verification for OWL compliance;
- **Appendix 9.1.** List of publications;
- **Appendix 9.2.** Selected journal publications.

2. AN OVERVIEW OF SUSTAINABLE BUILDING TECHNOLOGIES

2.1 General

This chapter presents an overview on the application of sustainable building technology in building development projects. An investigative approach is undertaken to establish why developers are reluctant to use sustainable building technologies in their projects despite their immense benefits. Based on the identified challenges in the uptake of sustainable building technologies, the chapter establishes the role advanced knowledge modelling and management techniques could play in overcoming the challenges. Thus, laying the groundwork for Chapter 3, where the semantic web technologies which can contribute significantly in knowledge modelling and management will be investigated. The chapter establishes the state-of-the-art of sustainable building technologies which constitutes the problem domain upon which the knowledge base, which is the core of this thesis, is developed.

2.2 Background

Today's legislative pressures, market forces, investor's concern and stringent customers' demands compel construction companies to re-assess their business strategies and adopt changes in current construction practices. One of the business strategies, top on the agenda of most business enterprises and governments is the implementation of sustainable construction practices including the provision of services, use of sustainable building materials, delivery and implementation of technologies. As well as having direct impacts on the environment, the aforementioned practices are directly linked to the socio-economic aspects of companies (Egan 1998; Udeaja 2002). Given that the UK government is imposing caps on emission levels and rating buildings for environmental performance, the case for sustainability in construction projects becomes even stronger if companies are to achieve the required performance levels. Sustainable building technology is key to sustainable building practices of construction projects. While some countries in the West have made great advancement in the use of sustainable building technologies, UK construction companies are being criticized for being too reluctant and hesitant in incorporating sustainable building technologies into their projects (Tindale 2010; PHOB 2002; DEFRA 2010; Barlow *et al.* 2003).

A recent report published by the Centre for European Reform (Tindale, 2010) states that success of the European Union (EU) to meet its renewables target will largely depend on the performance of big six countries, i.e. France, Germany, Spain, Italy, Poland and the UK. Currently the report suggests that of these countries, Spain performs best, with 20% of its electricity generated renewably, and followed by Germany (15%), Italy (14%) and France (13%). The UK (5%) and Poland (4%) stand out as the weak performers (Tindale, 2010). Analysis reveals that in 2000, 58% of the UK government energy Research and Development went to nuclear power while only 23% was spent on renewable energy (PHOB, 2002). When compared to Switzerland, Denmark, Spain, the US, Germany and Japan, the UK spent far less on renewable energy and development. In terms of recycling, UK is still very much lagging in comparison to other the European countries like Austria and Belgium, where more than 50% of their waste are recycled (DEFRA, 2010).

Studies have shown that a more sustainable future entails a clean environment, a safer, and more cohesive and inclusive society and will be economically more successful and resourceful (Pitt *et al.* 2009; Sayce *et al.* 2007; Barlow *et al.* 2003). In order to realise the full benefits of sustainable practices, construction companies need a change in current practices. One of the changes is by incorporating sustainable building technologies into building projects (Hall 2006; Whittingham *et al.* 2003).

2.3 Overview of the construction industry and climate change

The ultimate cry from the international community has been to stabilise greenhouse gas emissions at acceptable concentration levels. This is evidenced in outcomes of a number of international conventions such as the Kyoto Protocol and the Article 2 of the United Nations Framework Convention on Climate Change, just to list but a few. For the objectives of the above conventions to be attained, sustainable policies must be put in place to manage in a sustainable fashion, human processes, practices and exploitation of natural resources. As an overview of sectorial emission levels, recent studies by IPCC (2007) reveal the global anthropogenic greenhouse gas emissions by sector are as follows: waste and wastewater - 2.8%, energy supply - 25.9%, transport - 13.1%, agriculture - 13.5%, forestry - 17.4%, industry - 19.4%, residential and commercial buildings - 7.9%. However, focusing on CO_2 as the least potent but by far the most plentiful and the largest contributing compound in the greenhouse gas effect we can note that globally at 33%, the building sector is the second largest emitter of CO_2 gases (Ürge-Vorsatz and Novikova, 2008). This share rises to about 40% of CO_2 emissions across EU and about 50% in UK (BRE 2010; RICS 2005). The emission of greenhouse gases into the atmosphere is as a result of human activities largely driven by the desire for a more comfortable life. Unfortunately, these greenhouse gases are having undesirable long term and persistent impacts on the society as a whole (Stern 2006; Commonwealth Foundation 2007; Winkler 2005; IPCC 2007). As such sustainability concerns are no longer the pre-occupation of academics and pressure groups alone but have gained widespread acceptance internationally and triggered heated debates among practitioners on ways for devising and implementing sustainable development policies that can eventually halt and reverse global warming.

2.3.1 Sustainable development: What does it mean?

"Sustainability" is a highly contested word. The term has nonetheless become so ubiquitous in both public and private policy discourse that it can sometimes be viewed as becoming almost an otiose due to the many different interpretations and definitions of the terms and/or its adoption as politically expedient gestures. Indeed, it has been noted that there are over 200 different definitions of the term (Parkin 2000; Parkin *et al.* 2003). If defining sustainable development is difficult, then implementation in practice is even harder. Consequently, there is a serious concern that the issue has become so vague, contested and indeterminate a concept that it is open to wide spread abuse by politicians and business people alike (Porritt 2005; Warner and Negrete 2005). Often the term is equivocally used more as a rhetorical charade to justify the status quo or absolute minimum measures that may be required by law rather than a real intention of changing their ways (Keivani *et al.*, 2010).

In fact the phrase "sustainable development" first came to notice in the "World Conservation Strategy: Living Resource Conservation for Sustainable Development" published in 1980 (Lee, 1994). It was, however, propelled to the front of the international policy agenda in 1987 following the publication of the report of the World Commission on Environment and Development "Our Common Future" otherwise known as the Brundtland Report, named after the chair of the commission, the then Norwergian Prime Minister (Our Common Future, 1987). However, it was five years later at the 1992 Rio Summit in Rio de Janeiro Summit hosting the United Nations Conference on Environment and Development, which more than 170 countries ratified the Brundtland report and offered a more refined definition that has become the main currency:

"To equitably meet developmental and environmental needs of present and future generations" (United Nations, 1992)

Perhaps one of the most useful and holistic definition of sustainable development is that of which comes under the banner of "triple bottom-line", a phrase that was first coined by Elkington (1998) and which will be defined conceptually as economic prosperity, environmental quality and social justice. This trio are the key components in the sustainable development agenda. It is within this context that the section 2.3.2 examines the significance of the UK construction industry with respect to sustainable development.

2.3.2 The significance of the UK construction industry vis-à-vis sustainability agenda

From an economic point of view, the UK construction industry is a major contributor and component to the national economy. Prior to the credit crunch of 2008 (GLAE, 2008), the UK construction industry represented about 10% Gross Domestic Product and employed about 2 million people (DTI, 2005). It has a strong multiplier effect and it is estimated that approximately 20% of all other types of employments are linked to the construction industry (RICS, 2005).

From a social point of view, the performance, quality and design of buildings including access to public and private services and recreations directly affect the quality of life, promotion of healthy living and a cohesive society. This assertion is further strengthened by a positive economic impact as discussed in the preceding paragraph.

High level employment entails high standards of quality living. On the contrary unemployment leads to family break downs, high level of societal ills and poor standards of living. Furthermore, the construction sector accounts for 9% of injuries at work. This requires stringent health and safety measures and better technologies to minimize the level of accidents on construction sites.

The impact on the environment is by far the most evident of the three components of sustainable development with respect to construction practices. The construction industry exerts enormous demands on global non-renewable natural resources, thereby contributing significant negative impacts on the environment. The provision of buildings and structures changes the nature, function and appearance of cities, towns and the countryside. Their construction, use, repair, maintenance and demolition consume energy and resources and generate waste on a scale which dwarfs most other industrial sectors. According to UNEP (2006), taking into account its entire lifespan, the built environment is responsible in each country for 25 to 40% of total energy use, 30 to 40% of solid waste generation and 30 to 40% of global greenhouse gas emissions. Areas of key concern also include production of construction materials, use and recycling, consumption of hazardous materials, integration of buildings with other infrastructure and social systems, water use and discharge, etc. In the case of the UK, water use, energy use and construction waste are important factors that impact negatively on the environment. These three factors are examined in the ensuing paragraphs.

Firstly, with regards to water use, for the last 30 years water consumption in the UK has experienced a drastic increase of about 70% (Brownhill and Yates, 2001). This condition will be further exacerbated given that the number of households in the UK is on the increase and due to the negative impact of climate change on water levels.

Secondly, with regards to energy use, the built environment is responsible for over 50% of the UK energy consumption (Mulholland *et al.*, 2006). The rise in UK energy consumption has been partly linked to the growing UK economy (Mulholland *et al.*, 2006). Though there has been a growing demand in energy use, studies reveal that about 30% of energy consumed in the UK is wasted (Mulholland *et al.*, 2006).

Thirdly, with regards to waste creation, estimates show that of the 420 million tons of materials used in the UK construction industry annually, 360 million tonnes are actually incorporated in the desired products (Osmani *et al.* 2006; del Río Merino and Gracia 2010). This statistic raises the following major concerns: the depletion of the already limited and finite natural resources (e.g. buildings consume 40% of materials of the world's economy and 75% of the world's timber), clients increasing demand for improved environmental performance, the high cost involved in waste disposal, the high spending of the UK construction industry on landfill tax and the fact that waste costs companies 4% of turnover (Osmani *et al.* 2006; Dainty and Brooke 2004).

Hence, from the above, the UK construction industry has a significant role to play in driving forward the sustainable development agenda. It has therefore been increasingly experiencing pressure from the community to address environmental and social concerns. In response to these demands, the sector is developing and adopting sustainable construction practices which build upon the principles of sustainable development. Like sustainable development it is hard to coin a precise definition for sustainable construction. However, it can be construed to mean building construction practices undertaken on the principles of sustainable development.

Many studies have actually demonstrated the role sustainable building technologies can play towards sustainable development (Whittingham *et al.*, 2003). Therefore, sustainable building technology is key to sustainable construction. From an environmental point of view, an example is the huge amount of energy and material saving that can be achieved through the use of sustainable building technologies in building projects. As argued by Rees (1999), sustainable building technologies have the potential to make an enormous contribution to a required 50% reduction in the energy and material intensity of consumption globally. The needed dematerialization increases to 90% in the high-income countries. Hence, it is worth looking at its significance with respect to the building sector. The reasons for choosing the building sector are on the one hand directly related to its sheer contribution towards greenhouse gas emission, waste generation, energy consumption, and water use previously examined in this document. On the other hand, the building sector offers the highest low-cost potential with regards to the implementation of sustainable building technologies as part of a global agenda of climate change mitigation (Ürge-Vorsatz and Novikova, 2008).

2.3.3 Sustainable building technologies and building development

Like sustainable development, technology is a highly contested word in the academic community. From the various definitions in Borgmann (2006) it can be argued that technology is the application of knowledge in building machines and processes that can be used for the achievement of some well-defined goals or to obtain a solution of a particular problem. Hence, the term "technology" encompasses not only the tangible physical tools or machines; it also engulfs non-tangible things such as processes, symbols used towards the achievement of a particular target. Thus, by combining the definitions of sustainable development and technology, "sustainable building technology" can be defined as a technology that fosters the goals of sustainable development. In fact, sustainable building technologies are practical technological solutions to achieve the economic, social development of the society but not at the expense of the environment.

Some studies reveal that the implementation of sustainable building technologies in construction projects contributes significantly to enhancing cost effectiveness, improving process, material, and product efficiencies (Katz 2003; Roaf *et al.* 2001; Chiras 2000). To this effect, to qualify as sustainable building technologies, solutions to be provided by these technologies must meet the triple bottom line components of sustainable development. Taking into account the various impacts of construction practices on the environment and the society as a whole, and the definition of sustainable development, modern methods of construction, water conservation technologies, renewable building materials, smart system technologies, waste minimisation technologies, and renewable energy technologies are technologies currently being incorporated into building projects.

The aforementioned list of sustainable building technologies is by no means exhaustive but it gives a holistic overview of the sustainable building technology domain. A summarised description of the sustainable building technologies will be examined in the ensuing sections. These will provide a backdrop against which to model knowledge about the sustainable building technology domain in Chapter 6.

2.3.3.1 Modern methods of construction

Many government papers and institutions have advanced various definitions as to what constitutes modern methods of construction. The most notable ones are the Parliamentary Office of Science and Technology (POSTnote, 2003), Burwood and Jess (2005), Energy Saving Trust (EST, 2005), Barker 33 Cross Industry Group (Barker 33, 2006), and the Office of the Deputy Prime Minister (ODPM, 2005). Although the difinitions advanced by these authors differ, they generally tend to agree on two main categories of systems as modern method of construction systems. These are the off-site manufacturing and non-off-site manufacturing modern methods of construction.

The main types of off-site manufacturing modern methods of construction are panellised, volumetric or modular, hybrid, sub-assembly systems and non-off-site manufacturing modern methods of construction. Panellised systems are factory-produced flat panel units assembled onsite to produce the 3-dimensional (3D) structure. The volumetric systems are factory-produced 3D units stacked onsite to form the dwelling. For example, a three bed-roomed semi-detached house would comprise four units excluding the roof. The hybrid system is a combination of both the volumetric and the panellised units/systems. Sub-assembly systems are factory-produced items not regarded as full systems but they replace parts of the structure normally fabricated onsite. Some examples are pre-fabricated floor and roof cassettes. Non-off-site manufacturing modern methods of construction are innovative site-based forms of construction. Examples include in-situ concrete constructions such as tunnel form and thin joint block-work.

Although there are some concerns about the cost viability of modern methods of construction when compared to traditional methods of construction (Blismas *et al.*, 2006), some disadvantages with the former still exist such as transportation cost over longer distances, transport restrictions as seen on road signs may limit height in space, traffic jams, and the risks associated with the transfer of the products to site. However, studies have revealed that the advantages of modern methods of construction far outweigh their disadvantages (POSTnote 2003; Ross 2005; Hall 2006). Some of the advantages are fast return on investment, health and safety savings, time savings, quality savings, efficiency savings, material savings, fewer defects and fewer mistakes.

2.3.3.2 Water conservation technologies

Water conservation technologies are technologies aimed at reducing the usage of water and recycling of waste water for different purposes like cleaning, washing, drinking, etc. After the post-war period, there has been an increasing trend in the demand for domestic water consumption per capita in the UK (Sim *et al.*, 2007). The main drivers of this upsurge in demand are increases in population, household numbers and reduction in household size (Sim *et al.*, 2007). According to the report by Sim *et al.* (2007) water conservation technologies could play a key role in minimising water wastage. Some key water conservation technologies already available in the UK markets are greywater technology, rain water harvesting, very low flush toilets, waterless technologies, reduced pressure showers, efficient dish washers and baths, regulating domestic water flow, metering, green roofs, etc. Among all these technologies, greywater and rainwater recycling have the greatest water saving potential of approximately 75 litres/person/per day compared to the year 2001 standard appliance (Sim *et al.*, 2007). Hence, only these two technologies will be considered in this study.

Greywater recycling refers to the appropriate collection, treatment and storage of used shower, bath and tap water for use instead of potable water in Water Closets and/or washing machines (CLG, 2006). Greywater recycling technologies are systems used in the greywater recycling process. There are two main advantages of greywater. First, a greywater system has a constant supply as it does not depend on external phenomena such as rain. Secondly, the substitution of potable water with greywater used for purposes other than drinking reduces demand and thus assists in the preservation of valuable water resources.

2.3.3.3 Renewable building materials

The total material consumed in the UK from all sectors amounts to approximately 678 million tonnes per annum (Dunster *et al.*, 2009). Of this amount 420 million tonnes of materials are used in construction projects (Dunster *et al.*, 2009). This translates to more than half of material resource use by weight! Some studies reveal that around 50% of all global resources go into the construction industry, with a specific example being that 70% of all timber is used for building. It is therefore important to carefully select materials that are environmentally benign. Some key performance indicators considered for selecting construction materials are carbon impact level, embodied energy emission level, thermal characteristics, greenhouse gas savings, lifespan, toxicity and recyclability. Detailed studies about the different building material performance indicators are outside the scope of this study. However, an illustrative example on embodied energy of different materials is provided for clarity on how construction materials can be selected. Embodied energy is energy used in producing a given construction material (Roaf *et al.*, 2001). Timber tends to generally have very low embodied energy compared to plastics and metals with very high embodied energy (Roaf *et al.*, 2001). Therefore, in a building project, and assuming all other factors are constant, timber frame could be preferred over metal frames because of its low embodied energy content.

2.3.3.4 Smart system technologies

Smart building systems are integrated communication technologies fitted or installed in a building to monitor and manage the performance of the building and support the lifestyle choices of the occupant (Nicholl and Perry, 2009). In the literature, different appellations have been used interchangeably with smart building systems. The two most common ones are intelligent building systems (Robin, 2005) and brainy building systems (Morris, 2006). Despite the different appellations being used for smart building systems, they have one main goal - that of monitoring and managing the building's performance. Put differently, building smart systems are equipped with capabilities to monitor the environmental, social and economic performance of a building. From an environmental point of view, smart building systems can estimate CO_2 emission rate levels of a building. From a social point of view, smart building systems can be used to provide services that meet the future needs of occupants in case their life style changes. An example is a panic alarm installed in bathrooms to raise the alarm when an elderly occupant falls. From an economic point of view, smart building systems can minimise the use of services in a building leading to a significant reduction in waste and cost. An example is the use of light sensors in a building that will only light when there is an occupant and will automatically turn off when there is no occupant.

2.3.3.5 Waste minimisation technologies

Waste minimisation technologies in buildings are technologies that are used in reducing or eliminating waste in a building. Depending on the building types waste could be classified as commercial, industrial, office and household waste (DEFRA, 2010). A vast majority of waste from buildings ends up in landfills. Waste in landfills has serious negative environmental impacts. For example, in each region of the UK, for every one tonne of diverted landfill waste, 600 000 tonnes of CO_2 emission is saved in a year (DEFRA, 2010). The increasing scarcity of landfills, pollution and emission control currently being imposed by the UK government makes waste minimisation technologies a better alternative to deal with waste and to comply with the governments control strategies. Hence, waste minimisation technologies have emerged and most have been developed with regards to the waste management hierarchy, a key part of the government waste management framework. The waste hierarchy has five key elements namely in decreasing order of preference: prevention, minimisation or reduction, re-use, recycling, recovery and disposal (DEFRA 2010; WasteOnline 2010). It is recommended that this hierarchy be implemented in waste management techniques during the use of common waste management technologies such as anaerobic digestion (WasteOnline, 2010), incineration (POSTnote, 2000), pyrolysis and gasification (DECC, 2010).

2.3.3.6 Renewable energy technologies

The current UK energy supply sector constitutes about 38% greenhouse gas emissions (Allen *et al.*, 2008). Approximately 65% of the primary energy is lost as wasted heat during the production of electricity using centralised production system (Allen *et al.*, 2008). Renewable energy technologies have the potential to dramatically reduce these losses because when fossil fuels are used, the heat generated by localised electricity production can be captured and utilised for space and water heating. Heat and electricity can also be produced locally by renewable sources. Another great importance of renewable energy source is the fact that it is carbon neutral (Hall 2006; Allen *et al.* 2008). A renewable source is said to be carbon neutral if the amount of CO_2 emitted during the sourcing of the energy is off-set with an equivalent amount sequestered or removed from the atmosphere.

The UK government has been proactive towards the reduction of greenhouse gases such as CO_2 emissions. For instance, and as discussed in section 1.3, the nation is now legally bound to the Kyoto protocol to reduce its CO_2 emissions by at least 12.5% below the 1990 levels between the 2008-2012 time frame (Stolarski *et al.*, 2010). Furthermore, the UK Government's Climate Change Act 2008 sets a legally binding target of 80% reduction in national CO_2 emissions by 2050 compared to 1990 levels (DECC, 2009). To achieve these targets, and at the same time providing affordable and clean energy to buildings, mitigation strategies including the use of renewable energy technologies is being recommended by the government (DECC, 2009). Some common renewable energy technologies in the UK are combined heat and power, geothermal, hydro, tidal, wind, wave and solar energy systems.

Combined heat and power (Biomass): is a community heating and electricity system that generates fuel derived from biomass or organic matter. It is important to note that combined heat and power is renewable only when dedicated crops or forest used or where replanting occurs. In this case the carbon captured during growth will be equal to the carbon emitted during combustion. Combined heat and power has a primary energy conversion of 80% compared to a normal grid supply of 30-40 % (Allen *et al.*, 2008). If widely used, it can lead to significant CO_2 reduction.

Geothermal energy systems: refer to systems that capture energy from the earth's core. It has a potential in the UK, although it requires an electrical input which, with the current electricity mix will be only partially renewable.

Hydro energy technologies: are technologies that use energy from moving water, usually by channelling water at high pressure from the top to the bottom of a dam or by making use of river flows to drive an electricity generator.

Tidal systems: generate electrical energy by exploiting tidal water flows. Tidal systems can be realised by constructing a tidal barrage in an estuary and operating it as a conventional hydro dam. The UK has the largest tidal resources in Europe, i.e. about 50% of the EU's tidal resources (Kaszewski 2009; Tindale 2010).

Wind systems or wind turbines: are renewable energy technologies used in generating energy from wind in motion. The UK has the largest potential wind energy resource in Europe (SDC 2005; Tindale 2010). The UK possesses 35% of the EU's wind resources (Kaszewski, 2009).

Waves: transmit large volumes of energy from windy conditions far out to sea. Hence, the potential of wave energy in the UK is very enormous due to its coastline. Studies reveal that the UK wave resource is estimated to be 15% of current UK electricity demand (Kaszewski, 2009).

Solar energy systems: are systems that harness energy from the sun. Currently in the UK, this energy is used in three main ways, passive heat, solar thermal and PV-system. As already explained in section 1.5.1, part of this study focuses on PV-system. Consequently, the PV-system will be examined in more detail in the ensuing section.

2.3.4 Photovoltaic systems

2.3.4.1 An overview of the photovoltaic system

PV 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 back-plate, thus, forming a weatherproof enclosure. Modules are often grouped into arrays. PV 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 PV-systems use different semiconductor materials and manufacturing techniques. PV-system installations have a wide variation in outputs and are thus, rated according to their peak power output (kWpeak or kWp). PV-systems can be grid-connected or they can be stand-alone. A typical 'grid-connected' system allows the installation to put power into the building's mains electricity supply in parallel with the local grid. When the building demands more electricity than the PV-system can provide, the grid provides the 'top-up'. When the PV-system is generating more energy than the building needs, the excess is exported to the grid. The key component in such a system is the inverter, which converts the PV-system-generated direct current (DC) into alternating current (AC), and does so in synchrony with the mains. Grid-connected systems require very little maintenance, 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 for other system components, such as batteries. Prices for PV-systems vary, depending on the size of the system to be installed, type of PV cell used and the nature of the building on which the PV-system is mounted. The size of the system is dictated by the amount of electricity required.

2.3.4.2 The description of major components of the PV-system

Studies by Jungbluth *et al.* (2009), Roaf *et al.* (2001) and Chiras (2000) reveal that the PV-system domain is a knowledge intensive domain. Thus, it is necessary to establish clear definitions, boundary and scope of study about the different concepts to be considered. Some of the major areas reviewed in this study are the different types of PV-system, the different PV-array material type, the domain of application of the PV-system, the specific location where the PV-system is implanted, and the major components of PV-systems.

The two main categories of PV-systems in the UK markets are the grid-connected and the non-grid connected. As earlier mentioned in the overview section, the latter contains an additional component for storage of electricity, i.e. the battery. For illustrative purposes this study examines a grid connected stand-alone DC-AC system. The different components of a stand-alone DC-AC PV-system is captured and presented in Figure 2.1.

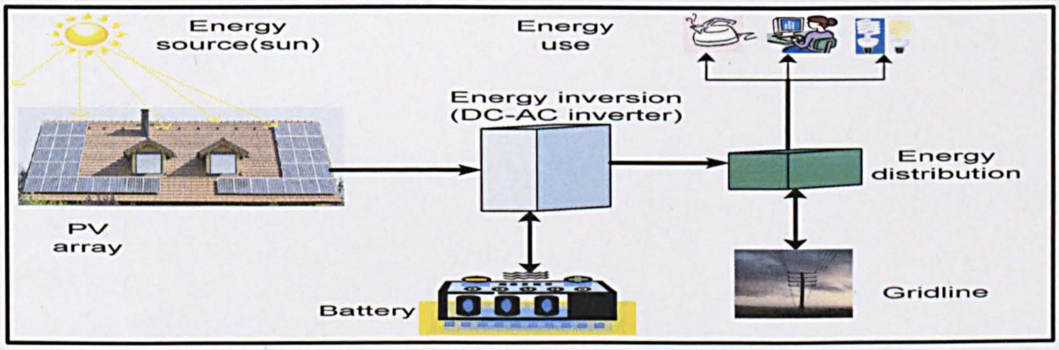

Figure 2.1. Grid-connected, stand-alone DC-AC PV-system
[Source: (Tah and Abanda, 2011)]

The most important component for any PV-system is the PV-array shown in Figure. 2.1. The constituent elements of the PV-array are made from different materials with silicon being the most widely used. The three main types of technology considered in this study are the monocrystalline, polycrystalline and amorphous silicon cells. These three were chosen because of their popularity in the UK PV-system market.

Monocrystalline silicon cells are made using a slice from a single crystal and are the most efficient but the most expensive. Polycrystalline silicon cells are cheaper, but they are less efficient compared to monocrystalline silicon cells. This is because polycrystalline cells are made from silicon cast in a mould. The thin-film amorphous silicon is cheaper but less efficient than both the mono and polycrystalline silicon cells.

The choice of the material type leads to different efficiency and hence different material types may be more convenient with different applications. For instance, due to roof size constraints, a monocrystalline PV-array may be more suitable than the polycrystalline and the thin film amorphous silicon. In the literature the different application areas are solar power plants, electricity supply to villages (in developing countries), residential or domestic buildings, water supply plants, commercial buildings, government buildings, etc. (Jungbluth *et al.*, 2009). For reasons explained in section 1.5.1, this study focuses on the application of PV-systems on any type of building.

In practice, PV-systems can be mounted on the roof tops, integrated with the roof, implanted on an open-ground or integrated on the building façade. In the case of the PV-system mounted on the roof, there is a visible extension that often distorts the aesthetics of the roof. While in the integrated case, the PV-system is integrated with the roof construction and thus replaces the normal cover. The open-ground are all PV-system power plants which are not erected on existing buildings. The PV-systems are implanted on the bare ground at a distance away from the building. In addition to the above fixed PV-systems, there is a mobile PV-system aimed at optimising the capture of the solar radiations. This type is often called the panel tracking PV-system. The PV-array of this system is adjusted according to the angle of tilt of the sun so as to optimise the capture of the sun's radiation.

In the preceding sections, the scope and boundary has been defined. This has been done with respect to the building types, material type, location of the PV-system, and the type of PV-system. Given the scope of this study, it was imperative to state the components to be included. From the design point of view many components are involved in the design of a complete PV-system plant. Some are inverters, batteries, cables, fuses, charge controllers, etc.

The PV-array is one of the most important components of a PV-system. This is because it is the gateway through which solar energy is captured and converted into other energy types for use in a given application. For clarity, the main components of a PV-array are presented below in Figure 2.2.

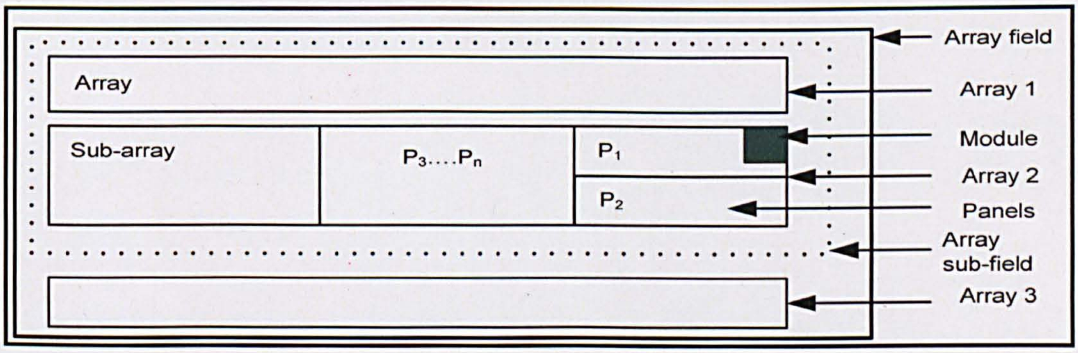

Figure 2.2. The structure of the PV-array field

Figure 2.2 depicts the module, the panel, the array, the array sub-field, and the array field as the main components of a PV-array.

The module is the smallest complete environmentally-protected assembly of interconnected solar cells. The panel is a group of modules fastened together, pre-assembled and wired designed to serve as an installable unit in an array and or sub-array. A sub-array is a part of an array assembly that can be considered as a unit and constitutes a component of an array. An array is a mechanically integrated assembly of modules or panels together with support structure, but exclusive of foundation, tracking, thermal control and other such components to form a DC power-producing unit. An array field is an aggregate of all solar PV-arrays within a given system. An inverter is needed in most residential PV-systems for the conversion of the DC power from the array to AC power. The size of the inverter often depends on whether the PV-system is a stand-alone or whether base loads are going to be matched. In general, an inverter consists of the following parts: transformers, electronic components and some connectors. The detailed description of these components is out of the scope of this study.

These technologies and their advantages cannot be exhaustively listed in this thesis. However, given that these advantages are already well documented (Pitt *et al.* 2009; Egan 1998; POSTnote 2003; Ross 2005; Waskett 2001; Hall 2006; Barlow *et al.* 2003; Dewick and Miozzo 2002; Sayce *et al.* 2007) a summary of some of the main advantages are discussed in the ensuing section.

2.3.5 Advantages of sustainable building technologies

The advantages of sustainable building technologies can be categorised into the energy efficiency, material efficiency, water efficiency, health and safety, waste reduction, greenhouse gas emission reduction and economic factors.

The implementation of sustainable building technologies and measures can lead to energy savings in buildings. A building can be rendered energy efficient by introducing measures such as using high energy efficiency components (such as windows, insulation walls, ceilings, and floors), using renewable energy technologies, and using modern methods of construction. Construction material efficiency can be achieved by implementing modern methods of construction (Hall 2006; POSTnote 2003; Ross 2005). Water savings can be achieved by implementing water savings and water conservation technologies such as greywater, rain water harvesting, ultra low-flush toilets, low-flow shower heads, and other water conserving fixtures (Hall, 2006). Many building construction materials contain products that emit toxic gases, such as volatile organic compounds (VOC) and formaldehyde. Sustainable building materials minimises the occupants' health impact such as reduction in the rate of respiratory disease, allergy, asthma, and sick building symptoms (Pitt *et al.*, 2009). With respect to safety on construction sites, the implementation of modern methods of construction can significantly reduce accidents onsite since most of the construction process takes place in the factory under strict engineering or factory controlled conditions (POSTnote 2003; Ross 2005; Egan 1998). Furthermore, the implementation of modern methods of construction can significantly reduce onsite construction waste (Ross 2005; Waskett 2001; Barlow *et al.* 2003).

The reduction in the emission of greenhouse gases is the most widely acknowledged benefit of sustainable building technologies in construction projects. The renewable energy technologies, modern methods of construction, water conservation, water and waste minimisation technologies all contribute to the reduction in the emission of greenhouse gases in construction projects. The most ambiguous advantage of sustainable building technology is the cost factor. Many studies are inconclusive as to whether the use of sustainable building technology in construction projects is less costly than constructing without incorporating sustainable building technologies. It should be noted that most of these studies do not take into consideration or quantify factors such as improving occupants' health, comfort, productivity, reducing pollution and landfill waste. However, detailed studies by Blismas *et al.* (2006) and Katz (2003) reveal that the implementation of sustainable building technologies in construction can be cost-effective if factors such as occupants' health, comfort, productivity, pollution and landfill waste are quantified and taken into consideration. This cost benefit cannot be maximised if all the quantities including factors such as occupants' health, comfort, productivity, pollution and landfill waste are not determined at the design stage of the construction.

2.3.6 Disadvantages of sustainable building technologies

Despite the numerous advantages examined above, there still exist some significant disadvantages. These are well documented and, just like the advantages, they largely depend on particular sustainable building technology. However, rather than address the disadvantages individually, this section will examine the two most significant disadvantages common to almost all the sustainable building technologies. These are performance measurement and cost of sustainable building technologies.

The importance of sustainable building technologies in buildings will be greatly appreciated if their performance can be measured. Performance measurement is important for ensuring that sustainable buildings meet the environmental targets claimed for them and to assess ways to improve those targets (Katz, 2003). However, efforts to measure the performance of sustainable building technologies are not yet well-developed for most elements (Blismas *et al.*, 2006). Some, such as energy and water use, are comparatively easy to measure quantitatively, for example through metering. Others may be difficult to quantify and may be possible to evaluate only on the basis of the presence or absence of certain features or through other more qualitative measures (Ding, 2008). The lack of means to measure the performance of sustainable building technologies often leads to underestimation of their importance.

Currently, the initial costs of most sustainable building technologies are generally still not very affordable (Keirstead, 2005). However, the reasons for the higher costs are difficult to discern because most project financial information is commercially confidential (POSTnote, 2003). It may be that the costs are high because some benefits of using sustainable building technologies such as better quality are not often reflected in project accounts. For example, the high quality of off-site manufactured buildings and the few or limited number of onsite accidents compared to traditional buildings is not often considered in cost. However, proponents of sustainable building assert that operational cost savings will eventually recoup any initially higher investment.

2.3.7 Challenges in the uptake of sustainable building technologies

The UK has long recognized the need for its construction industry and other sectors to consider sustainability as a top agenda item in all its businesses endeavours. At the international level, the UK has demonstrated its commitment to sustainability through its engagement in many world initiatives aimed at mitigating climate change impacts including the 1992 Earth Summit (United Nations Conference on Environment and Sustainable Development), The Kyoto Protocol (DTI, 2004), the G5 and G8 summits (G8 2006; Florini and Sovacool 2009; Onoda 2009) and the COP15 (Stern 2009; TSO 2009). Furthermore, at the national level, the UK is committed in sponsoring climate change related research through the provision of grants to local authorities and companies to embark on the sustainability agenda. The government also initiates awareness-raising programmes on climate change impact. Some notable institutions championing research in the domain of building construction and climate change are the Energy Saving Trust, the Carbon Trust and the Building Research Establishment.

Despite the above efforts by the UK government, it has been noticed that its construction industry is still lagging behind many other countries such as Germany, France, Sweden, Denmark, The Netherlands and Japan with regards to the mitigation of climate change impacts. In particular, the UK construction industry has been very slow and reluctant in the uptake of sustainable building technologies in its construction projects (Egan 1998; Hall 2006; Barlow *et al.* 2003; Dewick and Miozzo 2002; Sayce *et al.* 2007). In the literature, different barriers have been advanced as reasons for the uptake of sustainable building technologies including high cost, lack of knowledge about the different technologies, ambiguity in the issuance of planning permits, and too much information about the different technologies, etc. (Egan 1998; Hall 2006; Barlow *et al.* 2003; Dewick and Miozzo 2002; Sayce *et al.* 2007). While the above list is inexhaustive, with respect to the focus of this study, only information and knowledge related barriers will be examined.

2.3.7.1 Fragmentation of the industry

While the construction industry has been noted as one of the industries that contribute significantly towards lessening greenhouse gas emission, it is however highly fragmented in structure and often project-based. Due to the fragmented structure and project-based nature of this industry, the effective adoption of innovation, especially sustainable building technology requires the participation and collaboration of all stakeholders in the industry. In the construction industry, most sustainable building technologies stem from upstream product manufacturers and suppliers of the building products. However, all parties in the building supply chain have certain responsibilities to promote their adoption and use (Dewick and Miozzo, 2002). It is the responsibility of the client to specify the use of the technologies that reduce the consumption of resources over the lifetime of a building and to consider the life cycle costs in addition to the capital costs. It is the responsibility of the engineer and the architect to interpret the client's requirements to include technologies that improve the design of the project. And finally, it is the responsibility of the contractor to include technologies that improve the buildability of the project. For instance, these improvements can be sustainable, involving a clean and efficient production process, use of low embodied energy materials and waste minimisation. One of the most common barriers for the implementation of sustainable building technologies is the lack of flow of information between project partners. This has often been termed the "vicious cycle of blame", a situation where each stakeholder in the industry blames another for not playing their role towards sustainability (Taylor and Wilkie, 2008). As a summary to highlight the lack of flow of information in delivering sustainable building technologies between partners (occupiers/clients, constructors, developers, suppliers, investors) (adopted from Taylor and Wilkie, 2008), the main concerns of the "vicious cycle of blame" are examined in the ensuing paragraph:

- Investors believe there is no demand for sustainable building technologies, so do not fund them;

- Occupiers or clients would like sustainable building technologies, but claim they cannot make a choice;

- Constructors can build or install sustainable building technologies, but claim developers and/or clients have not asked for them;

- Suppliers can provide sustainable building technologies, but claim clients and developers are not willing to pay for them.

The simplified scenario amongst stakeholders involved in the delivery of sustainable building technologies serves to illustrate that the construction process could undoubtedly benefit from improved flows of information between stakeholders. As argued by Taylor and Wilkie (2008), the circle of blame could be broken or would not exist if the flows of information between the stakeholders were established. Increased level of collaboration and feedback could be used to educate and inform mutual benefit. Such an information flow network would potentially provide a framework for the delivery of superior and more appropriate sustainable building technologies.

2.3.7.2 Lack of knowledge about the real benefits of sustainable building technologies

Some studies reveal that the housing developers lack knowledge about the different cost of the different sustainable building technologies. Recent studies by Oxera Consulting (Oxera, 2006), one of Europe's foremost independent economics consultancies reveal that a major factor affecting consumers to make decisions on the uptake of energy efficient technologies is the lack of knowledge about the cost. For example, the actual costs of implementing installation measures without taking into account subsidies from the European Economic Community vary between £265 for a flat and £550 for a detached house for cavity wall insulation. However, many observers believe the costs to be more than £500 to £1000 higher than the actual costs. Furthermore, many clients lack knowledge about the benefits of sustainable building technologies (Oxera, 2006). A major factor affecting the ability of consumers to make decisions on the uptake of sustainable building technologies is the lack of knowledge about the benefits of these technologies (Oxera, 2006).

2.3.7.3 Abundance of information over the web

One of the highest media being used by the construction industry in publishing information is the current web. The use of the web in publishing information about sustainable building technology has also gained ground. There are many online services for the listing of suppliers, installers, and the different sustainable building products available in most markets. Some examples are Green Book Live website (GBL, 2010), YouGen (YouGen, 2010), and the Energy Saving Trust. This huge amount of information about these technologies has been overwhelming to interested end-users although they find it increasingly difficult to maximise the use of sustainable building technologies over the web. This situation is further being exacerbated by guidelines and legislation about the different technologies. In order to highlight these problems about the way information about sustainable building technologies are managed in current web system, some cases have been investigated. Real-world examples of websites that contain sustainable building technology knowledge will constitute good cases for investigation. Three examples of current web systems for the selection of sustainable building technologies and their suppliers within the UK building sector are examined. The examples describe the processes involved in finding or selecting sustainable building technologies and their suppliers. The websites, being among the best websites in the UK, also reflect the challenges in the selection processes based on the current web technologies. The examples presented have been analysed with respect to their background, the organisational aspects, and the use of current web techniques. The websites are those of YouGen, Energy Saving Trust and Green Book Live.

Example 1: YouGen

YouGen is a web-based social enterprise being operated as a limited company. It was started in 2008 and aims at providing detailed information about micro-generation technologies including their suppliers (YouGen, 2010). The website assists individuals in finding and choosing the right renewable energy technologies for purchase. This is achieved by:

- Providing compiled research information about a wide range of sources on renewable technologies;
- Providing excerpts about PV-systems from energy experts;
- Information sharing and supplier recommendations;

- Identifying individuals that have installed a particular technology, and its local suppliers;

- Allowing companies to add information about their technologies .

A screenshot of the YouGen website depicting renewable energy technologies is presented in Figure 2.3.

Figure 2.3. YouGen renewable energy technology taxonomy

Example 2: The Energy Saving Trust

The Energy Saving Trust is a non-profit organisation that provides free and impartial advice about micro-generation technologies. Energy Saving Trust provides information about the latest emerging renewable energy technologies in the UK. Furthermore, it provides advice on how grants, funding and financing options can be obtained for the different renewable energy technological options. A screenshot of the Energy Saving Trust website depicting renewable energy technologies is presented in Figure 2.4.

Figure 2.4. Energy Saving Trust renewable energy technology taxonomy

Example 3 The Green Book Live example

Building Research Establishment (BRE) is an independent research-based consultancy, testing and training organisation offering expertise in a wide range of aspects within the built environment and associated industries (BRE, 2011). BRE provides an open source database, called Green Book Live, designed to help specifiers and end-users identify products and services that can help to reduce their impact on the environment. Green Book Live contains a list of names of organisations and provides comprehensive information on green products and services. Furthermore, it provides approved and stringent environmental requirements (GBL, 2010). Specifiers and end-users can use Green Book Live in selecting different green building products and services which can be used in buildings (GBL, 2010). Green Book Live contains a wide range of products and services, from commercial building products and services to domestic energy efficiency products. A screenshot of the BRE website depicting renewable energy technologies is presented in Figure 2.5.

Figure 2.5. BRE renewable energy technology taxonomy

As can be seen from Figures 2.3, 2.4 & 2.5, sustainable building technologies are classified as what is often called vertical product classification (Antonio and van Harmelen, 2004): the products are classified under a vertical column and separate rows. For example, from Figure 2.5, the column is made up of heat pumps, pellet stoves, photovoltaics, small scale hydro-turbines, solar thermal, wind turbines, wood-fuel boilers and heat-led-cogeneration package technologies. This type of classification constitutes what is commonly called lightweight ontologies in the ontology community (Gómez-Pérez *et al.*; 2004; Studer *et al.* 1998). For example, from Figure 2.5, the BRE renewable energy technology can be represented as in Figure 2.6.

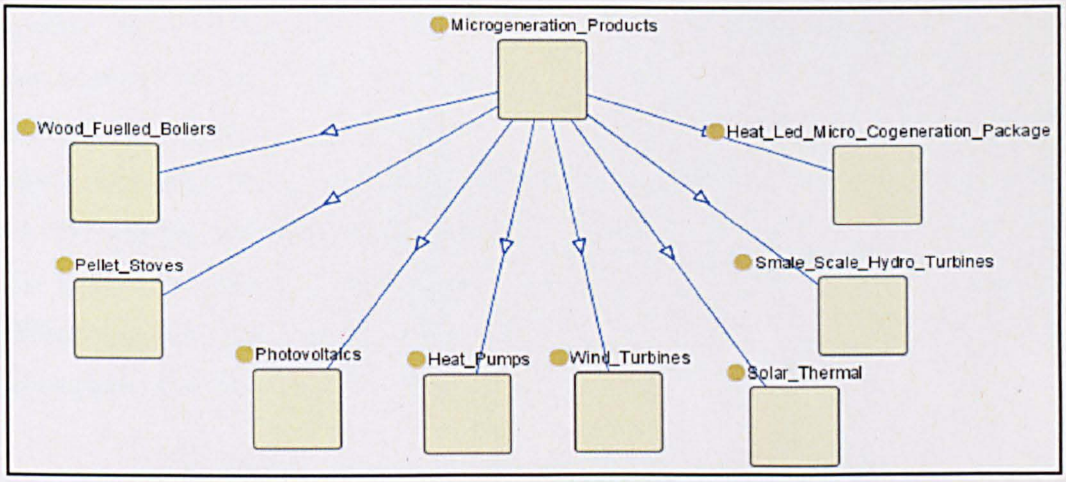

Figure 2.6. Graphical view of BRE renewable energy lightweight ontology

The YouGen, Energy Saving Trust and BRE format of presenting information about sustainable building technologies as lightweight ontologies is very useful from a perspective of those who know the technologies and want to know or find information about the desired technologies. However, with the emergence of too many specifications and with many governments obliging companies to adhere to these specifications, the traditional division of information into concepts is no longer satisfactory. Clients, who may be interested in any sustainable energy technology, are first interested in a certain specification or constraint that spread across the common sustainable energy technology taxonomy provided by suppliers. For example, a client may be interested in "carbon-saving" energy technologies, regardless of which of the sustainable energy technologies meet this criterion. The interest of the clients can further be complicated by placing more constraints such as the "highest carbon-saving" and "cheapest" renewable energy technologies.

Although the above three organisations provide a starting point to identifying emerging green building technologies, they are still very limited in providing real information to the level that can facilitate decision-making in choosing alternative technologies. These three sites provide a list of alternatives certified suppliers for end-users to choose from. When a choice is made, the end-user is directed to the suppliers' websites where different information about the different technologies is presented. There are three challenges faced by end-users in the selection process of a given technology using any of these websites. Firstly, although most of the suppliers listed by these websites are certified, end-users have to browse through them without any guidelines on who is the best supplier. Secondly, after identifying a supplier, the end-user will have to browse through the supplier's website and list of products. Thirdly, suppliers provide information about the different technologies using different formats. The format is often not standardised and very challenging for an end-user to make use of the information. The birth of YouGen was actually as a result of the frustration of its founder browsing different website about sustainable building technologies, yet not finding any concrete information about the technologies.

2.3.7.4 Too many synonyms and definitions

In the domain of sustainable building development, many different experts work together. Their disciplines of expertise are surveying, civil engineering, environmental engineering, construction engineering, construction and project management, computer science, environmental science, structural engineering, research, etc. These experts work with different organisations including research consultancies, universities, construction companies, suppliers, installers, non-governmental organisations, government agencies, etc. Influenced by experts' background, each organisation uses a particular vocabulary (a precise common terminology does not exist) in specifying the different terminologies in the domain of sustainable building technologies. Hence, many jargons used by different authors to mean the same thing or simply put, these words are more like synonyms. Some terms can be used in different disciplines with similar, but not identical meanings (semantic differences appear using the same term in different disciplines). For instance, sustainable building is variously known as green building (Korkmaz *et al.*, 2010), environmental friendly building (Lagerstedt *et al.* 2003), eco-building, environmentally benign manufactured building, environmental conscious building (Jeswiet and Hauschild, 2005). The use of synonyms reflects the need for the creation of a unified, complete and consistent terminology which can be used in different formal contexts and applications related to the sustainable building technology domain. Although the use of synonyms will always exist especially in a construction domain, the exploitation of these synonyms over the current web poses serious challenges with respect to web searches. This will be further investigated as part of the limitations of the current web techniques in Chapter 3. As highlighted in sections 2.3.1 and 2.3.3.1, so many concepts are being defined differently by different authors. Some examples are the definitions of sustainable development which has over 200 definitions; modern methods of construction have at least 5 definitions. These different definitions have often led to different classifications. This is a problem that is also challenging from an information point of view in the sense that two or more different taxonomies are used in the specification of a particular domain.

2.3.7.5 Lack of clear guidelines in choosing the different sustainable building technologies

The potentially devastating threat of climate change is making the specification of green building products more and more urgent (Green Building Store, 2010). However, the plethora of guidelines and legislation regulating the sustainable building technologies ranging from building regulations to building code for sustainable homes has made the selection of products a highly complex process (Green Building Store, 2010). In the literature, most of these standards do stipulate the minimum or maximum requirement to be achieved by a given building. However, although some of these requirements from standards are mandatory they do not provide an exact combination of technologies to use in achieving the standard. Also this is the general practice over the web by different suppliers who publish information in mostly qualitative and quantitative formats. Generic expressions like "a PV-system is cheaper", "a PV-system does not emit CO_2", and "PV-systems are highly energy efficient" are quite common. Although such qualifications are very informative they lack concrete means of providing a demarcation of how to choose a given sustainable building technology over the other or even how to select a product based on some criteria of choice.

What emerges from the foregoing exposition is that advanced knowledge technologies could play a crucial role in triggering the uptake of sustainable building technologies and yet very little attention has been paid to them.

From the perspective of lack of collaboration between project partners which hinders information flows, research in this direction has been gaining ground. For example, El-Diraby *et al.*(2005) developed a semantic web representation of construction knowledge which supports effective collaboration and for virtual teams of skilled users to exchange ideas and make decisions about best practices.

With respect to the existence of different definitions, different taxonomies and different synonyms that characterise the sustainable building technology domain, ontology engineering offers a great opportunity to flexibly model these characteristics of a domain representing different definitions and appellations from different perspectives or from different authors. For instance, modelling ontologies using Mentodology (to be reviewed in Chapter 3) provides a way of dealing with synonyms.

One of the set-backs about current information in most literature about the sustainable building technologies is that most properties of sustainable building technologies are presented by using mostly qualitative qualification. The way these properties are presented does not provide a great way of exploiting them for decision-making purposes. The use of specifications in defining requirements to be fulfilled by sustainable building technologies suffers from the same set-back like properties of sustainable building technologies.

After over 20 years of implementing information and communication technology into building construction, there is no doubt that substantial progress has been achieved, but real improvement in terms of speed and consistency are lacking (Rees, 2006). As argued by Rees (2006), and by the strengths of the semantic web demonstrated by Davies *et al.* (2006), Alesso and Smith (2009) and from success stories of exemplar projects in other fields such as bioinformatics and e-commerce, could the semantic web be the missing technology the building construction industry should have had to cure its myriad knowledge management problems? Moreover, the present WWW used by many professionals has made a huge amount of information available and has been a success story in terms of availability of information and growth rate of the number of (human) users. However, the success and exponential growth of information and number of users have rendered the web increasingly difficult to find, to access, to present, and to maintain information for use to a wide variety of users (Fensel *et al.* 2005; Lacy 2005; Antonio and van Harmelen 2004).

To overcome the limitation of the current web technology, the semantic web, the next generation of the web technology has gradually gained prominence in the scientific research community. As defined by its creator Berners-Lee: *"the semantic web is an* *extension of the current web in which information is given a well defined meaning, better enabling computers and people to work in co-operation* (Berners-Lee *et al.*, 2001)*"*. The next chapter focuses on an overview of the semantic web technologies.

2.4 Conclusion

This chapter has reviewed the domain of sustainable building technology. The review was undertaken from three perspectives. In the first perspective, the role of sustainable building technologies could play in mitigating climate change impacts was established. This was done by identifying current practices in the UK construction industry vis-à-vis their impact on the environment and opportunities that exist if sustainable building technologies are implemented. In the second perspective, it was argued that despite the opportunities in sustainable building technologies, its uptake has been very slow, it was established that the non-agreement on a common vocabulary of terms, classification, fragmented nature of the building industry, lack of information flows were major barriers. Furthermore, the involvement of so many stakeholders publishing documents in so many different formats rendered knowledge acquisition for making informed decisions complex. In the third perspective and based on the above two perspectives, the review established that there is need for investigating the use of semantic web technology, an advanced knowledge technology in modelling knowledge about sustainable building technologies. The challenges are which aspects of the semantic web technologies can be used in modelling sustainable building technologies? What aspects of the sustainable building technologies should be modelled? How should the final output of the modelled knowledge of the sustainable building technology knowledge be presented? These challenges will be investigated in Chapter 3.

3. AN OVERVIEW OF SEMANTIC WEB TECHNOLOGIES AND KNOWLEDGE ENGINEERING

3.1 General

The previous chapter has established the role knowledge can play in advancing the use of sustainable building technologies. The chapter also highlighted the apparent need for exploring advanced knowledge techniques for managing sustainable building technology information. This chapter now explores how the semantic web technology can be used in developing applications aimed at promoting the uptake of sustainable building technologies. Given that the semantic web is an emerging technology, the approach of the review in this chapter is an exploratory one. The chapter is technically categorised into three main parts. The first part examines the different aspects of the semantic web technologies, taking into consideration their strengths and weaknesses. This part consists of sections 3.2 - 3.16. Based on the different semantic web technologies examined in the first part, the second part presents a summary of the key technologies to be used in this study. The second part is examined in section 3.17. As most of the discussions including how and why the different semantic web technologies have been chosen in sections 3.2 - 3.17, the last part is the conclusion section, which is a summary of the entire chapter.

3.2 Background

The invention of the WWW has been a great success story in the information world. The WWW has enabled an exponential growth of both electronic documents and users over the web. Estimates reveal that by 2007 the web contained about 3 billion static documents and was being accessed by over 500 million users from around the world (Bui *et al.*, 2007). This exponential growth is partly as a result of businesses scrambling over information and posting information about their businesses over the web for different goals. Today, it is not uncommon to find millions of agents in different geographical locations sharing common information over the web about the same or different domain of interest. Nonetheless, the efficiency of sharing information using the current web technology is still very debatable. Its very success has been the cause for its inefficiency. This partly explains the recent surge in studies by the semantic web research community, with many researchers interested in technologies that can sufficiently enhance the capabilities and efficiency of current web technology. No wonder the inventor of the current web technology is at the fore-front of this research about semantic web technologies. Just like the research community, many industries have demonstrated keen interest in the opportunities embedded in semantic web technologies. Some notable examples of the application of the semantic web are in the fields of publishing, judiciary, bioinformatics, finance, and energy (Antonio and van Harmelen 2004; Warren *et al.* 2006). The importance of semantic web technology to business houses and the information society partly underpins the rationale for this study. Like other industries, the construction industry cannot afford to miss the opportunities and promises of semantic web technology. However, in order to reap the benefits of these opportunities and promises, a deep understanding of semantic web technology and its potential for application to the sustainable building technology domain is imperative. The logical starting point of a review of the semantic web is to examine the current web which is the focus of the ensuing section.

3.3 The current web technology

From historical perspectives, information technology has undergone tremendous changes. Based on the examination of these changes by Alesso and Smith (2009) each generation of information technology builds on or exploits the gaps of the previous generation. Hence, this section will examine the last generation corresponding to the years after 1990 when the current web was invented (Alesso and Smith 2009; Gillies and Cailliau 2000; Berners-Lee 2000). Prior to the invention of the web, the era was generally known as the information age which was characterised by the rise of computing and was all about the building of databases (Applehans *et al.* 2000; Alesso and Smith 2009). This shifted to what was/is known today as the era of the information economy where there is a merge between computers and communication to enhance connectivity. Just as the industrial revolution leading to economic growth was accompanied by staggering amount of pollution, the information economy is characterised by what is generally referred to as infoSmog or information overload (Applehans *et al.* 2000; Ulmer 2006). Information overload and the exponential growth of web users are the main causes of the inefficiencies surrounding current web technology. These limitations have now been well documented (Mika 2007; Yu 2007) and they include imprecision in information search, maintenance of web resources and the presentation of information.

3.3.1 Imprecision in information search

Searching for a piece of information on the current web is a task that can be quite frustrating and daunting. The web user is often drowned in the huge amount of irrelevant material that is obtained when a key word search is undertaken in Google (the most popular search engine). Furthermore, current web searches multiply one's chances of missing the relevant materials as the searches are very often imprecise and do return thousands of irrelevant pages which are not only confusing but also become complex as the web grows. Even when the relevant pages are found, they require thorough reading for the rightful information to be elicited.

3.3.2 Maintenance of web resources

The current web lacks or has very limited capabilities in keeping redundant information correct and consistent. This is quite daunting to webmasters who cannot cope with managing this huge redundant, incorrect and inconsistent information. Hence, it is not uncommon today to find many websites with inconsistent and contradictory information.

3.3.3 Presentation of information

The current web is too document-centric in the way it represents information. Most of the documents over the web are semi-structured HTML (a syntactic language suitable for visual presentation hence the current web is often called the syntactic web) documents containing unstructured text. Though this mode of publishing information is effective from the human point of view, it is not effective with machines. Such information representation modes cannot support automatic computer processing. Of course automatic information processing will enhance scalability and will reduce the work load to be executed manually by humans.

The above limitations of current web technology explain why the current web can no longer provide services to humans as required. As will be further highlighted in the next section that provides an overview of the current web search techniques, search results from the current web are not so accurate.

3.4 Current web search techniques

The review of current web techniques will serve two main purposes. Firstly, it is used to identify the weaknesses of current web search techniques and their applications. Secondly, the scope and focus of this research work are developed based on the identified weaknesses and on the findings from the exploratory study of the semantic web. Based on an extensive literature review the weaknesses of the current web can be categorized into four groups, vis-à-vis the exact match methods, the vector space approaches, the statistical or probabilistic approaches, and the natural language processing.

In the literature many search techniques have been suggested and classified under the above four main groups. Key words and region models techniques are common types of exact match search techniques (Hiemstra, 2009). The vector space model (Salton and McGill, 1983), the relevance feedback algorithm (Rocchio, 1971) and the vector term weighting (Salton 1971; Salton and Yang 1973) have been classified as vector space approaches. The probabilistic indexing technique, the probabilistic retrieval model, the 2-Poisson model, the Bayesian network models, the automatic speech recognition model and the Google's PageRank models are examples of statistical or probabilistic approaches of search techniques. The last but not the least consists of the natural language processing group.

In the context of this study and given that the above search techniques have been reviewed in the literature, the focus of this chapter will be to examine the relevant common techniques that are appropriate in the context of semantic web. In this regard, the keywords and the Google PageRank models will be reviewed, focussing on the knowledge gaps. This will lead to the review of the natural language processing as search techniques that improves upon the weaknesses of the former two techniques. The foundation of the ontology and the semantic web search techniques will be built from the knowledge gaps identified in the natural language processing techniques.

3.4.1 Keyword search

Keyword search is a database operation that involves a client who sends queries consisting of keywords and receives records associated with them (Freedman *et al.*, 2005). Keyword technology has been used in different forms for quite sometime. It was first used by International Business Machines (IBM) in its free text retrieval system in the late 1960's. The tool developed by IBM was based on a simple scan of a text document to find a key word or a root stem of a word. With the advent of the internet many leading search engines such as Google, Excite, Lycos and WebCrawler have been used by companies for information retrieval about their business activities and products. This has been done using keyword searches in documents or web pages which must have been defined or embedded in the document or web page, often in the <Meta> tag. The <Meta> tag is an HTML element used in a web page to embed information for use by a search engine. Many companies have developed intranets and it is not uncommon to find that one major way of dynamic content retrieval of company's information is by using keywords (Ingirige and Sexton, 2007). However, keyword search technology has been proven to be very inefficient (Hanhua *et al.* 2008; Hassan *et al.* 2004). Some common problems associated with keyword searches are: 1) false negatives (no matches found because the word or stem are not exactly identical, e.g. "lift" and "elevator", "average" and "mean"); b) false positives (too many unrelated matches found because a root stem has found many unrelated words, e.g. "string" and "stringent"); and 3) scalability (the huge amount or long list of documents from search engines when keyword queries are submitted is a huge problem for end-users especially if the data base is very huge).

3.4.2 Google search algorithm

Google is undeniably the most popular commercial search engine available today. At the heart of the search engine is the PageRank, a system of ranking web pages developed by its founders Larry Page and Sergey Brin at Stanford University, USA (Alesso and Smith, 2009). The basic idea of PageRank is that if a page *i* has a link to a page a and the author of i is implicitly endorsing a, i.e., the author of page i has given some importance to page a. How much i contributes to the importance of a is proportional to the importance of i itself. The Google PageRank algorithm assigns a numeric rank denoting its importance to every document in a system. The intuition behind the PageRank algorithm is based on the *random surfer* model. A user visiting a page is likely to click on any of the links with equal probability and at some random point, may decide to move to a new page. The PageRank of a web page is defined by equation 3.1:

Equation 3.1. Google PageRank search formula

$$P(a) = 1 - d + d * \sum_{i/i \to a} \frac{P(i)}{C(i)} \qquad 3.1$$

[Source: Adapted from Argüello *et al.*, 2006a]

Where $P(a)$ is the PageRank of a web page a, $P(i)$ is the PageRank of the page i, $C(i)$ is the number of outbound links out of any page i, $i \to a$ denotes the i's for which the $P(i)$ value for which page a receives from page i and d is the damping factor in the range $0<d<1$, usually sets to 0.85. Therefore, the PageRank of a web page is dominated by the sum of the PageRanks of all the pages linking to it (its incoming links) divided by the number of links on each of those pages (its outgoing links).

However, this search technique is inefficient as it heavily relies on the vast link structure as an indicator of an individual page's value and not in the content of the page (Argüello *et al.* 2006a; Alesso and Smith 2009).

3.4.3 Natural language processing

Presently there is no universal agreement as to what a natural language is. However, based on a review of the literature the common denominator of the various definitions is that natural languages are languages such as Swahili, English, French, etc. against computing or programming languages such as Pascal, C++ and Java. The main aim of natural language processing is to generate natural language from a computer representation system such as a knowledge base. Natural language processors often understand basic grammatical structure such as "nouns-verbs", "subject-verb-object", "adjectives", "adverbs", "articles", etc.

Hence, a natural language processor can understand the difference between sentences that include nouns-verbs, subject-verb-object, adjectives, adverbs and articles. Therefore, a natural language search engine would in theory find targeted answers to user questions (as opposed to keyword search). An example of natural language search engine is the contemporary WolframAlpha Computational Knowledge engine developed by Wolfram Research Institute in London, UK (Johnson, 2009). The search engine attempts to address some of the deficiencies of the current web search engines by understanding people's questions and answering them directly. For instance, typing the question "Where is the UK?" in WolframApha yields an exact result of UK as a location. But if the same question was asked in the case of other engines like Google, a cocktail of confusing and weird results (6.08 million results for a search conducted at 18.00 hours on 9 September 2010) would be generated, including, for example, the title "Welcome to the Home Office". Furthermore, Wolfram Alpha points to the UK as a location on the world map. On the other hand common search engines handle simple questions as quantum, or unordered sets of words, e.g. "Where is the UK?" Google treats it as if the end-user typed "UK", or "is the UK" leading to unexpected and often not useful results from pages with "UK" or "is the UK". Search results will also increase by day as more stuff containing words "UK", "is the UK", etc. are uploaded on the net every day. This scenario is even worse as common search engines such as Google have not been designed to deal with natural language questions (Roussinov *et al.*, 2008). Nonetheless the greatest set-backs of natural language processors are that they suffer from semantic symmetry and ambiguous modification problems (Joshi and Akerkar, 2008). These will be examined through the use of adjectives in sentences as discussed in the ensuing paragraphs.

Semantic symmetry occurs when an entity is used as a subject as well as an object in different sentences (Joshi and Akerkar 2008; Katz and Lin 2003). Natural language processing uses keyword matching based on entities such as subjects, objects, adjectives, verbs and adverbs as parts of a sentence. The following example adopted from Joshi and Akerkar (2008) illustrates the problem posed by semantic symmetry.

Question: Who killed militants?

Candidate answer 1: National army soldiers killed six militants.

Candidate answer 2: Militants killed 13 bus passengers.

Comparing the above sentences with the generic structure of a sentence, i.e. subject_verb_object, "Militants" is an entity that acts as a subject in answer 2 and as an object in answer 1. The selection restriction for the subject of "kill" is word "Militants" in one sentence and the selection restriction for the object is also the word "Militants" in another sentence.

Thus, the question fetched two candidate answers on the basis of keyword matching and both sentences have altogether different meanings. More examples of semantic symmetry sentences are presented in Table 3.1.

Table 3.1. Examples of semantic symmetry sentences

The bird ate the snake	The snake ate the bird
The manufacturer supplied the PV-system	The PV-system was supplied by the manufacturer
The Germans defeated the French	The Germans were defeated by the French
President of the US visited the Gulf of Mexico	The British Petroleum chief visited the President of the US

With regards to ambiguous modification, if a paragraph contains a pool of adjectives and nouns, any particular adjective could potentially modify many nouns (Joshi and Akerkar 2008; Katz and Lin 2003). Hence, in natural language processing adjectives are often called ambiguous modifiers. It is difficult for systems to achieve high precision without a full understanding of the exact relationship between nouns and verbs in a sentence. The following query will be used to demonstrate the phenomenon of ambiguous modification adopted from Joshi and Akerkar (2008).

Question: What is the largest volcano in the solar system?

Candidate answer 1: The Galileo probe's mission to Jupiter, the largest planet *in the solar system*, included amazing photographs of the *volcanoes* on Io, one of its four famous moons.

Candidate answer 2: Even the *largest volcanoes* found on Earth are puny in comparison to others found around our cosmic backyard, *the solar system.*

In the above example, "largest" is the adjective which acts as modifier in adjective-noun relationships, where as in the solar system it is used to specify scope. Candidate answers 1 and 2 are correct at the lexical level, but wrong at the meaning level. In candidate answer 1, *largest* modifies the incorrect head noun. In candidate answer 2, *in the solar system* does not modify the correct head noun.

There is a common consensus to the acknowledgement of the existence of the above problems. Little wonder the research community is grappling with finding ways of addressing these problems. Hence, it is not uncommon to find various governments and business houses funding semantic web research. An example is the most widely used ontology editor Protégé developed by Stanford Center for Biomedical Informatics Research at the Stanford University School of Medicine. The Protégé project received funding from the Defense Advanced Research Projects Agency , eBay Inc., National Cancer Institute, National Institute of Standards and Technology, National Institutes of Health's National Centers for Biomedical Computing , National Library of Medicine and the National Science Foundation (Protégé Team, 2010).

So far, research in this domain reveals that the solutions to the above problems require that there be a machine-processable semantics for some or all of the information presented in the web (Berners-Lee *et al.*, 2001). This requires developing languages for expressing machine-processable meta-information for documents and terminologies, developing tools and new architectures that use such languages and terminologies to provide support in finding, accessing, presenting and maintaining information sources and realising applications that provide a new level of service to the human users of the semantic web (Fensel *et al.*, 2005). This is holistically referred to as "the semantic web architecture".

3.5 The Semantic web architecture

Based on the diverse nature of the different technologies being developed as part of the semantic web vision, a step-by-step approach has been adopted towards the development of the semantic web (Antonio and van Harmelen, 2004). Each step builds a layer on top of another. The justification to this approach is that, with the semantic web being an emerging technology, it is easier to achieve a consensus on small steps; whereas it is much harder to get everyone on board if too much is attempted (Antonio and van Harmelen, 2004). So far the different layers of the semantic web architecture are as in Table 3.2.

Table 3.2. Semantic web architecture*

Layer 6	Implementation layer	Applications	
Layer 5	Logical layer implementation layer	Ontology languages (OWL full, OWL DL, OWL lite)	
Layer 4	Ontological primitive layer	RDFS	Individuals
Layer 3	Basic relational layer	RDF and RDF/XML	
Layer 2	Syntax layer	XML and XMLS Data-types	
Layer 1	Reference layer	URIs and Namespaces	

[OWL: Web ontology language, OWL DL: OWL Description Logics, RDF: Resource Description Framework, RDFS: RDF Schema, XML: eXtensible Markup Language, XMLS: XML Schema, URI: Unified Resource Identifier]

The semantic web architecture constitutes the building block for the semantic web in the development of a meaningful web. The ensuing paragraphs examine briefly the key components of the semantic web architecture and how they can be used in defining ontologies and knowledge bases specifically for the web.

The reference layer provides identifiers and references to objects being described in ontologies and instance files through the use of URIs and XML namespaces.

The syntax layer is made up of the XML and XMLS data types. XML is a meta-language for specifying syntax only, with no semantics. XMLS defines standard data-types. Though XML provides features for representing and interchanging information, it lacks the capability or the semantics to support semantic web requirements. XML

* Adapted from Lacy (2005)

defines syntax not semantics and its descriptions are ambiguous to a computer. This led to the formulation of RDF.

The basic relational layer is made up of the RDF and RDF/XML. RDF provides the semantic web's basic relational language layer of data representation. It can be used to make statements with attributes/value pairs that describe objects. It introduces some standardisation to descriptions and more complex semantic relationships to objects in a domain. However, RDF is unable to completely support the semantic web in the sense that it does not provide sufficient expressiveness (it lacks the concepts of enumeration and data-types other than typed literals) for ontology descriptions, hence the necessity for a more powerful language, the RDFS.

The ontological primitive layer is made of RDFS. RDFS extends RDF by adding more features and provides the standard vocabulary for data model items. Like RDF, RDFS does not provide sufficient expressiveness to provide ontology descriptions required to support the semantic web. It does not support inferencing highly required by the semantic web. Hence, an advanced language, the OWL is necessary for this task.

The logical layer is made up of OWL dialects which are ontological languages used for the specification of classes, properties and related restrictions. OWL is designed for use by applications that need to process the content of information instead of just presenting to humans (McGuinness and van Harmelen, 2004). OWL comes in three dialects, i.e. OWL Lite, OWL DL and OWL Full (McGuinness and van Harmelen 2004; Horridge *et al.* 2007).

- OWL Lite supports those users primarily needing a classification hierarchy and simple constraints. For example, while it supports cardinality constraints, it only permits cardinality values of 0 or 1;

- OWL DL supports those users interested in the maximum expressiveness while retaining computational completeness (all conclusions are guaranteed to be computable) and decidability (all computations will finish in finite time). OWL DL includes all OWL language constructs, but they can be used only under certain restrictions (for example, while a class may be a subclass of many classes, a class cannot be an instance of another class). OWL DL is so named due to its roots in DL, a field of study upon which OWL DL is built;

- OWL Full is meant for users who want maximum expressiveness and the syntactic freedom of RDF with no computational guarantees. In other words, OWL Full is undecidable as it does not include restrictions on the use of transitive properties required to maintain decidability (Horrocks *et al.*, 1999). For example, in OWL Full, a class can be treated simultaneously as a collection of individuals and as an individual in its own right. OWL Full allows an ontology to augment the meaning of the pre-defined (RDF or OWL) vocabulary. It is unlikely that any reasoning software will be able to support complete reasoning for every feature of OWL Full. Based on the facts that OWL Lite is limited in capturing class hierarchies in ontologies and also that OWL Full is unlikely to have reasoning software to support complete reasoning of OWL, this study adopts OWL DL. In addition to this, there exist several reasoning plug-ins that can support reasoning with OWL DL. Furthermore, the semantic knowledge base designed in this study requires some types of inferencing beyond just reasoning between objects in a class hierarchy to meet the requirements of interested users.

Finally, the application layer is the last layer and represents applications or systems built using knowledge represented in OWL. From the point of view of end-users this layer constitutes the most important component of the semantic web architecture because it exploits the capabilities of the previous layers in the development of any system. A system here is simply defined as a set of components that interact with each other to solve a problem (Dietel and Dietel, 2009), e.g. knowledge bases and databases. In the computer science domain, the development of systems is a gradual progression from the client's initial vague ideas about the problem, via a series of transitional stages to a completely formal statement, expressed in a programming language which can be executed on a machine (Britton and Doake, 2005). This process entails elicitation of data and information from clients, representing the information into knowledge models suitable for humans and machines in formats that can be accessible by humans and/or machines. The process of data and information elicitation and transformation into useful knowledge models cuts across three main important fields, i.e. software engineering, knowledge engineering and the emerging ontology engineering. Each of these domains is quite vast and cannot be reviewed in any greater detail in this study. However, because knowledge and ontology are directly related, with ontology development being a sub-task of knowledge-based system development, a review of both domains will be undertaken.

3.6 Knowledge engineering

Before defining what constitutes knowledge engineering, it is important to first establish the concept of knowledge and its associated and often confusing terms such as *data, information, knowledge, knowledge representation* and *knowledge acquisition.*

Data is usually defined as unorganised and unprocessed facts. Information is defined as an aggregation of processed data that facilitates decision-making. With regards to knowledge, there are numerous definitions of knowledge with little or no agreement on definitions as to what constitutes knowledge. It is not the aim of this study to put a premium on the various, rather conflicting theories of knowledge, but instead adopts the definition that suits the purpose of this study. According to the Oxford English Dictionary, knowledge is defined variously as (i) expertise, and skills acquired by a person through experience or education; the theoretical or practical understanding of a subject, (ii) what is known in a particular field or in total; facts and information or (iii) awareness or familiarity gained by experience of a fact or situation. These definitions lead to the conclusions that information is obtained from data and knowledge can be obtained from information.

Like the ambiguity in the definitions of knowledge, knowledge representation and knowledge acquisition are not straight forwardly defined. Generally speaking knowledge representation is the relationship between two domains (Brachman and Levesque, 2004). The first domain is usually the representor and is more concrete while the second is more of an abstract concept. Knowledge acquisition includes the elicitation, collection, analysis, modelling and validation of knowledge for knowledge engineering and knowledge management projects (Milton, 2003). An example of a knowledge engineering or a knowledge management project is the development of a knowledge-based system. Knowledge engineering therefore is a branch of artificial intelligence that deals with the development of knowledge-based systems. In other words knowledge engineering deals with the building up of computer programs that solve problems the way humans do (Milton, 2008). Such programs contain huge amounts of knowledge, rules and reasoning mechanisms that software agents can use in addressing real life problems. The ensuing section presents a review of knowledge engineering methodologies.

3.6.1 Knowledge engineering methodologies

There exist many knowledge engineering methodologies for developing knowledge-based systems. Some major ones are Methodology for Knowledge-Based Engineering Applications (MOKA) (Stokes 2001; Skarka 2007), 47 Step-procedure (Milton, 2007), TOGA (Gadomski, 2008) and Common Knowledge Acquisition and Documentation Structuring (CommonKADS) (Schreiber *et al.*, 2000). The review of these methodologies reveals some similarities in the steps used in building knowledge-based systems. The implementation of any of the methodologies is likely to achieve similar results in a given project though some challenges linked to each methodology could emerge. However, some methodologies have more elaborate steps such as the 47 Step-procedure (Milton, 2007) methodologies consisting of, as the name suggests, forty seven steps, while some have very few steps such as the CommonKADS and MOKA with only six and three steps respectively. In this study, CommonKADS was adopted as the core methodology. This is because CommonKADS is currently the leading de-facto standard for knowledge analysis and knowledge intensive system development (Schreiber *et al.*, 2000). The major steps of the CommonKADS used in developing knowledge-based systems are knowledge identification, knowledge specification and knowledge refinement.

3.6.1.1 Knowledge identification

Knowledge identification is the first phase of the knowledge model construction using the CommonKADS methodology. The core activity in this phase is about acquiring knowledge that will finally be encoded in the knowledge model. This is often termed *knowledge elicitation.* In knowledge-based system domain, elicitation is variously known as investigation, fact-finding or requirements gathering (Skidmore and Eva, 2004). Elicitation can be seen as the process of acquiring material for use in a knowledge model (Schreiber *et al.*, 2000). Knowledge elicitation comprises a set of techniques and methods that attempt to elicit knowledge from a domain specialist through some form of direct interaction with an expert (Schreiber *et al.*, 2000). Depending on the type of knowledge (tacit or explicit) knowledge elicitation can be quite challenging and as such systematic techniques and procedures should be pursued. These include interviewing, questions and questionnaires, observation, protocol analysis, document analysis, workshops (Schreiber *et al.* 2000; Skidmore and Eva 2004). Using any of these elicitation techniques usually leads to an output of some structured data such as mark-ups, diagrams, list of terms, formulas and rules, etc. One important consideration in knowledge elicitation is the fact that the material acquired from different sources may not necessarily be "raw". For an efficient implementation of any or a combination of the elicitation techniques, the knowledge engineer should be familiarised with the domain of discourse, information sources and knowledge partners and key re-usable knowledge components identified.

3.6.1.2 Knowledge specification

Knowledge specification is the second phase of the knowledge model construction using the CommonKADS methodology. In this phase, the main task is the construction of a specification of the knowledge model. The first activity in the specification process is the identification and choosing of a task template. The second activity is the construction of the initial domain schema (i.e. product modelling or domain conceptualisation) or semi-formal modelling of the domain knowledge. The semi-formal modelling could be undertaken using any modelling language such as the UML. The re-usable components identified in the knowledge identification phase are taken into consideration in the construction of the initial domain schema. In terms of domain knowledge, the emphasis in this stage is on the domain schema and not so much on populating the knowledge base to be developed (Schreiber *et al.*, 2000). This can be set aside as a task in the knowledge refinement phase.

3.6.1.3 Knowledge refinement

Knowledge refinement is the third phase of the knowledge model construction using the CommonKADS methodology. Two main activities are undertaken at this stage, i.e. knowledge model validation and knowledge-based refinement. Knowledge model validation uses techniques such as paper simulation and prototyping. The main activity of the knowledge-based refinement is the completion of the knowledge base commenced in the knowledge specification phase. Knowledge refinement is the final phase of knowledge-based system development. Most of the processes need to be iteratively undertaken and validated in continuous processes until the desired outcome is attained.

The review of the phases of knowledge model development reveals that conceptual modelling or product modelling of the domain of discourse is an important task. Furthermore, because the execution of each phase may undergo several iterative processes, development of prototypes is often recommended before the development of a fuller version of the knowledge base. The ensuing section examines the conceptual modelling while prototyping development will be examined in section 3.16.

3.6.2 Object-oriented modelling using UML

A product model is a formally structured schema carrying product instance information that is generated and modified through the lifecycle of a product (Lee *et al.*, 2007). It is an abstract description of facts, concepts and instructions about a product or set of products. In any domain product models detail the internal and external facts about objects within the domain. It equally highlights the relationship between the objects in the domain. Hence, product models deal with the semantics of information as opposed to syntactic information. Consequently, product modelling has emerged as one of the best solutions to the industry's information technology problems. A product model does not only provide a clarified view of data about a product, it can also serve as a vehicle for integration (Ben-Ari and Yeshno, 2006). Hence, the major rationale for product modelling is the need to integrate computer-based applications in order to achieve the best performance (Ben-Ari and Yeshno, 2006). From a software engineering perspective, product models are object models which describe the structure of objects in a system; their identity, their relationships to other objects, their attributes and their operations (Scacchi, 2001). The main goal of product modelling is to capture concepts of a domain for use in an application. That is why in some literature, product modelling is often interchanged with conceptual modelling. In this study, the terms *product modelling* and *conceptual modelling* will be used interchangeably. Currently there are several techniques in modelling products of a particular domain (Udeaja, 2002) with each method being conditioned by the availability of information about the domain and the application to be developed from the models. This research adopts the UML as this is considered to be the most widely used language for product modelling and the de-facto industry standard for product analysis (Gašević *et al.* 2006; Booch *et al.* 2007).

UML is a graphical language that enables analysts and designers of object-oriented systems to visualize, specify, construct and document the artefacts of software systems and to model business organisations that use such systems (Bennett *et al.* 2005; Duc 2005; Booch *et al.* 2007). The UML is a standard language for writing software blueprints and it is a general-purpose modelling language that provides an extensive conceptual base for a broad spectrum of application domain. Consequently, UML has found widespread recognition and use in so many areas other than the domain of software development. Some notable areas are: computer games, e-commerce, banking, insurance, telephony, construction, robotics, etc. Recently it has been argued that UML should be used as a technique in bringing ontology development process closer to a wider community of practitioners (Gašević *et al.*, 2006). Interestingly, there is a close relationship between UML and ontology modelling techniques. It is now possible to re-use UML models to generate ontology models by using simple transformation languages such as Extensible Stylesheet Language Transformations (Hong-Seok Na *et al.*, 2006). In order to successfully model in UML, it is important first to understand the conceptual models of the language. The UML is a very huge domain and has been extensively studied and debated. For the purposes of this study, only concepts that will be used have been reviewed and presented in the ensuing paragraphs. The main concepts are: *things, class, relations,* and *diagrams*.

Things are the abstractions that are first-class citizens in a model. There are high-level concepts in a model. The sub-concepts of things are structural or static, dynamic or behavioural, grouping and annotational things (Booch *et al.* 2007; OMG 2009). For the purposes of this study structural, grouping and annotational will be reviewed. *Structural things* are nouns of UML models. There are mostly the static parts of a model representing elements that are either conceptual or physical. Grouping things are the organisational parts of UML models. These are the boxes into which a model can be composed. *Annotational things* are the explanatory parts of UML models. There are the comments that may be applied to describe, illuminate and remark about any element in a model.

A *class* is a standard UML construct used to detail the pattern from which objects will be produced at run-time (OMG, 2009). An object is an instance of a class. Generally a class is specified by its name, attribute and operation (Booch *et al.* 2007; OMG 2009). The attributes and operations of classes can be shown along with different kinds of relationships that bind the classes together. According to Tseng and Chen (2008), a class is a description of a set of objects that share the same attributes, operations, relationships and semantics. Classes may be inherited from other classes (i.e. they inherit all the behaviour and state of their parent and add new functionality of their own), have other classes as attributes and delegate responsibilities to other classes (OMG, 2009). This implies classes can be related to other classes.

Relations are used in joining things or classes together in a model. Generally four types of relations exist and are: *association, aggregation/composition,* and *generalisation.* These relations are the building blocks of UML and are used in writing well-formed models. An *association* is the structural relationship which specifies objects of one thing to be connected to objects of another (Booch *et al.* 2007; OMG 2009). *Aggregation/composition* is a type of association. An *aggregation* is a 'whole/part' relationship, in which the 'whole' class represents a larger thing, which consists of smaller things corresponding to the 'part' class (Bennett *et al.* 2005; Booch *et al.* 2007). To represent an aggregation, a line will be drawn to connect the 'whole' class and 'part' class, with an empty diamond on the 'whole' side. On the other hand, *composition* is a strict form of aggregation, in which 'part' class existence-dependent on the 'whole' class. Like in aggregation, a composition is denoted as a line between two classes, with a solid diamond on the side of the 'whole' class. A *generalisation* is an implementation for the relationship between superclass and subclass, such that the attributes and operations of a superclass are inherited by its subclasses (Bennett *et al.* 2005; Booch *et al.* 2007). A large empty arrow pointing from the subclass to the superclass is used in denoting such relationship. In some literature this type of relationship is often called 'is-a-kind-of' relationship. In a generalisation relation, all the attributes of the superclass are also enjoyed by the subclass. This is often called *inheritance*. Also in a relationship between any two classes, a natural number (0-n, n is a positive integer) could be used in defining the number instances of each of the classes is participating in the relationship. The number that defines the number of instances denotes what is often called the multiplicity of the relation. A common example of a multiplicity notation is the use of * for representing unspecified numbers. For clarity, the composition, aggregation and generalistion relationships are presented in Figures 3.1 & 3.2.

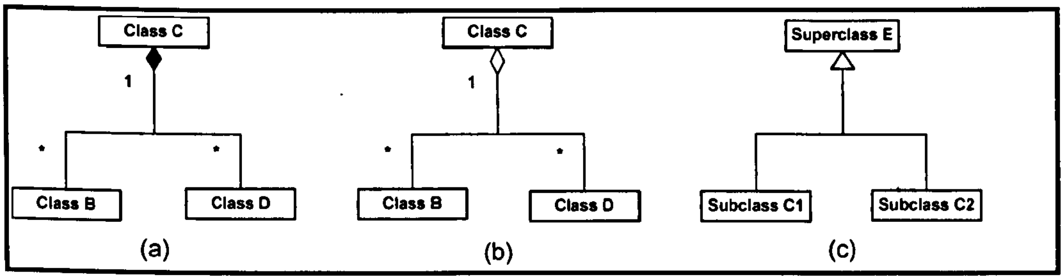

Figure 3.1. Relationships of (a) composition; (b) aggregation; (c) generalisation

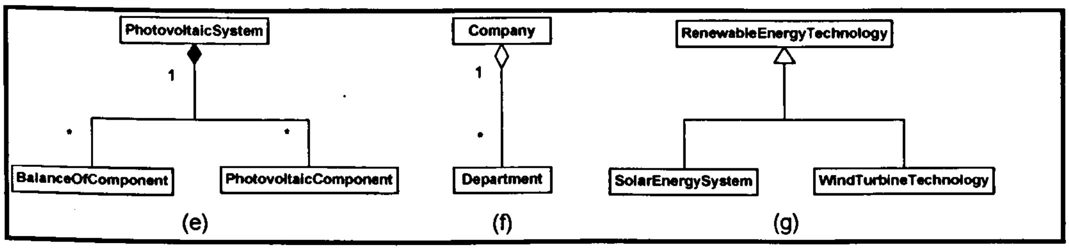

Figure 3.2. Examples of (e) composition; (f) aggregation; (g) generalisation

In Figure 3.2 above the following intepretations can be made:

- A PhotovoltaicSystem is composed of zero or many BalanceOfComponents and PhotovolaicComponents. As this is a composition relation, it means BalanceOfComponents and PhotovolaicComponents cannot exist without the existence of the PhotovoltaicSystem.

- A Company is composed of zero or many Departments. As this is an aggregation relationship it means the Department can continue to exist even if the Company no longer exists.

- SolarEnergySystem and WindTurbineTechnology are types of RenewableEnergyTechnology. As this is a generalisation relation, if it is asserted that RenewableEnergyTechnology is "energy efficient", then by deduction, both SolarEnergySystem and WindTurbineTechnology are also "energy efficient".

Diagrams are used in collecting things together. A *diagram* is a graphical representation of a set of elements, most often rendered as a connected graph of vertices or nodes (things) and arcs (relationships). *Diagrams* give a clear visualisation of a system from different perspectives. While there are different types of diagrams in the literature; this research reviews the class and the object diagrams required for the purposes of this study. A *class diagram* describes the types of objects in the system and the various kinds of static relationship that exist among them. It shows a static view of the classes in a model, or part of a model. It is often represented as rectangles. Figure 3.3 shows a typical building block for class diagrams, with basic features of class name, attributes and operations. An *object diagram* shows a set of objects and relationships. Object diagrams represent static snapshots of instances of things found in a class diagram (Booch *et al.* 2007; OMG 2009).

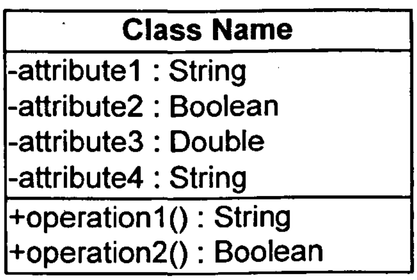

Figure 3.3. Building block for a sample class diagram

As earlier mentioned, when two classes involve the transfer of messages or data between them, they are associated to each other. The association relationship could be reciprocal. An example of an association relationship is presented in Figure 3.4.

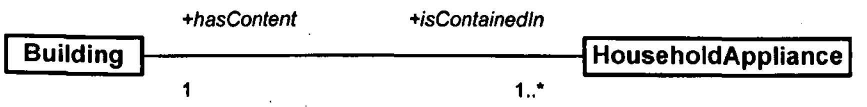

Figure 3.4. Association between classes

Figure 3.4 depicts an example of an association relationship. It can be interpreted as a Building hasContent of at least one HouseholdAppliance or one or many HouseholdAppliance *isContainedIn* a Building.

In summary the development of conceptual or product models employs *things, classes, objects* and *relationships*. However, the product models developed based solely on things, classes, objects and relationships have been accused of being insufficient and ineffective in capturing knowledge about any domain. Hence, the term traditional conceptual modelling has been coined by some researchers (Dillon *et al.*, 2008). The weaknesses of traditional conceptual modelling can be improved through the use of ontologies in what is often called ontological conceptual modelling, an aspect of ontological engineering to be reviewed in the ensuing sections.

3.7 Ontological engineering

Ontological engineering encompasses a set of activities that concerns the ontology development process, the ontology life cycle, the methods and methodologies for building ontologies, the tool suites and languages that support them (Gómez-Pérez *et al.* 2004; De Nicola *et al.* 2009). Currently, there is no general consensus regarding a common set of activities to be followed in building ontologies. This is partly due to the huge number of variables to be dealt with in a particular domain during the ontology development process (Breitman *et al.*, 2007). Consequently, different sets of activities proposed to deal with the above problems have emerged. This has resulted in the development of different tools, methodologies, methods and languages to support ontology development. Each of the approaches has been designed to address a particular domain problem and may not be absolutely suitable for application to other domains. In an attempt to understand the techniques and difficulties involved in each set of activities, this research presents some major methodologies, tools and languages used in ontology elicitation, modelling and construction processes.

3.7.1 Definition of an ontology

The definition of an ontology has been evolving over the years. Many different definitions have so far been coined depending on the philosophy of the knowledge community. Among these definitions, the most generally accepted and widely used definition is that of Gruber (1993) which states that *"an ontology is an explicit specification of a conceptualisation"*. In other words an ontology can be thought of as a specification of how the knowledge of a particular domain can be modelled (represented, described or structured) (Alesso and Smith 2009; Milton 2008). In modelling a particular knowledge domain, concepts are given well-defined meanings and the relationships between the concepts are well-established. The concepts, relationships, between the concepts and attributes of concepts in a particular domain constitute the main components of an ontology.

3.7.2 Why ontologies?

The main problem with information about most domains is the lack of semantics linking the terms or vocabularies in the various domains. This leads to high imprecision and the ambiguity of terms rendering the understanding of these terms difficult to be processed by machines and even humans to a lesser extent. Fundamentally, many useful features provided by ontologies aim to clarify and render knowledge about specific domains more precise and unambiguous. The main features provided by ontologies are: a common vocabulary, taxonomy of terms, knowledge sharing and re-use, and encoding of knowledge and semantics for use by machines. These features are examined in detail in the ensuing paragraphs.

An ontology provides a *vocabulary* (or the names) for referring to the terms in a subject area or specific domain (Gašević *et al.*, 2006). Two common problems often encountered in the use of natural languages are the use of two or more terms to mean the same thing and the use of one term to mean different things. For example, the terms *elevator* and *lift* are commonly used in the US and the UK respectively to mean the same thing. However, searching for the term *elevator* and *lift* in the Google search engine will yield different results or different web pages for both, giving the impression the two terms are different. This is simply because these two terms are not related semantically. In other words, Google is doing a purely syntactic search and does not recognise synonyms.

In the use of one term to mean different meanings, it is often difficult to identify which term refers to what, especially within the context of the current web system. For instance, how does one distinguish between the search results of the term OWL when used as a bird or as an Web Ontology Language when searched in the Google search engine? This term could bring thousands of pages about OWL as a bird or the Web Ontology Language or indeed as a name of sport teams (e.g. Florida Atlantic OWL), clubs (e.g. the OWL club of Harvard University) and other relevant acronyms (e.g. the UK-based software company Office Workstations Limited). Ontologies are different from natural language-oriented vocabularies in that they provide logical statements that describe terms in a domain and how the terms are related to each other. Furthermore, they specify rules for combining the terms and their relationships in defining extensions to the vocabulary.

A *taxonomy* is a hierarchical categorisation of concepts in a particular domain. The major difference between taxonomies as used in natural languages such as in most web pages and ontologies is that generalisation/specialisation (i.e. subclassing may not be included in the former). With ontologies, subclassing is strictly taken into consideration and is formally specified (Gašević *et al.*, 2006). Ontological formal specification includes formal instance relations which ensure consistencies in the use of ontologies for deductive reasoning.

With regards to *knowledge sharing and re-use,* the main purpose of ontologies is not only to serve as vocabularies and taxonomies; one of its major purposes is to facilitate the sharing and re-use of knowledge by various applications (Yu, 2007). For efficient sharing and re-use of knowledge a common understanding of the intended interpretations of terms in the domain of interest, and compatibility of the domain models used by different agents are imperative (Gašević *et al.*, 2006).

With regards to the *representation of knowledge and semantics*, the representation of ontologies using ontology languages such as RDF and OWL provides a way to encode knowledge and semantics such that machines can understand hence facilitating automatic large-scale information processing. The W3C semantic web standard suggests a specific formalism for encoding ontologies (OWL), in several variants that vary in expressive reasoning power (McGuinness and van Harmelen, 2004).

3.7.3 Types of ontologies

The main purpose of ontologies is not only to serve as vocabularies and taxonomies, but also to facilitate the sharing and re-use of knowledge. While this makes ontologies the key to the semantic web, there are no clear guidelines that can facilitate the choosing of an existing ontology for knowledge sharing and re-use. Often the notion of ontologies is diluted, in the sense that taxonomies are considered full ontologies (Studer *et al.*, 1998). For example, UNSPSC[†] , RosettaNet[‡] and the Yahoo (a taxonomy for searching the web) are considered as ontologies (Lassila and McGuinness, 2001) because they provide a consensual conceptualisation of a given domain. Hence, in the ontology community ontologies can be categorised into two groups. The first group are ontologies that are mainly taxonomies and are called lightweight ontologies (Gómez-Pérez *et al.*, 2004). The second category are ontologies that model a domain in a deeper way and provide more restrictions on domain semantics and are called heavyweight ontologies (*ibid*).

3.7.4 Ontology versus traditional conceptual modelling

Having reviewed both traditional conceptual models, and ontology conceptual models it is also important to draw some major differences/similarities between traditional and ontology conceptual modelling techniques. A full understanding of these differences would be significantly beneficial in developing ontology conceptual models. Firstly, the term *concept* used in ontology is similar to *class* and *entity* in object-oriented modelling. Secondly, concept, class and entity all have attributes and also participate in

† The United Nations Standard Products and Services Code® (UNSPSC®) provides an open, global multi-sector standard for efficient, accurate classification of products and services.

‡ RosettaNet is a non-profit consortium aimed at establishing standard processes for the sharing of business information (B2B). RosettaNet is a consortium of major Computer and Consumer Electronics, Electronic Components, Semiconductor Manufacturing, Telecommunications and Logistics companies working to create and implement industry-wide, open e-business process standards.

relationships with peers. Nonetheless, there are major differences between these modelling methods which are summarised in Table 3.3.

Table 3.3. A comparison between ontology and object-oriented model[§]

An ontology model	An object-oriented class structure
Reflects the structure of the world	Reflects the containment of data and behaviour (encapsulation)
About structure of concepts	Often about behaviours
A concept is a collection of instances	A class is a blueprint for defining instances
Instances can be created at design and/or run-time	Instances or objects can only be created at run-time
A concept's property exists independently and can be subsumed	Behaviours are embedded in a class definition and cannot be used independently
A concept does not concern physical representation	A class specifies physical representation of data
Based on open world reasoning	Based on closed world reasoning
Natively support automated reasoning for knowledge	Does not natively support reasoning

Table 3.3 provides the fundamental differences between ontology conceptual modelling and traditional conceptual modelling. These two paradigms underpin the demarcation line between current web search techniques and semantic web search techniques. For instance, open world reasoning and closed world reasoning greatly determine the output of search results performed in systems developed using the two conceptual paradigms. Having reviewed current web search techniques, the next section will now look at semantic web search techniques.

3.8 Semantic web searches

The vision of the semantic web through its founder Berners-Lee (Berners-Lee 2000; Berners-Lee 2001) represents a dramatic departure from the previous generations of web applications. It also brought new perspectives towards knowledge technologies with respect to representation and inferencing (Uszkoreit 2005; Yoo *et al.* 2005; Fensel *et al.* 2005; Tighe and Tawfik 2008). However, the dramatic departure of the semantic web does not ignore the successes of the previous applications but uses them as a

[§] Adapted from Noy (2000) and Horridge *et al.* (2007)

foundation to build highly intelligent semantic processing tools. In a nutshell, therefore, semantic web processing incorporates statistical forecasting and natural language processing and enhances them with semantic processing tools. Semantic search seeks to improve accuracy by understanding the searcher's intent and the contextual meaning of terms as they appear in the searchable data-space, whether on the web or within a closed system, to generate more relevant results. Two types of search techniques have been identified in the literature. These are navigational and research (Guha *et al.*, 2003). The former is document-driven, and the user is using the search engine as a navigation tool to browse an intended document. This type of search is not relevant to semantic searches. In the latter, the user provides the search engine with a phrase which is intended to denote an object about which the user is trying to gather information. There is no particular document which the user knows about, that s/he is trying to get to. Rather, the user is trying to locate a number of documents which together will give him/her the information s/he is trying to find. The semantic search lends itself well here. Rather than using ranking algorithms such as Google's PageRank to predict relevancy, semantic search uses semantics or the science of meaning in language, to produce highly relevant search results (WIKI, 2011). In most cases, the goal is to deliver the information queried by a user rather than have a user sort through a list of loosely related keyword results. Other authors primarily regard semantic search as a set of techniques for retrieving knowledge from richly structured data sources like ontologies as found on the semantic web (Alesso and Smith, 2009). Such technologies enable the formal articulation of domain knowledge at a high level of expressiveness and could enable the user to specify his intent in more detail at query time.

To be of any practical use, natural language processing requires more than the ability to extract the parts of speech. The processor needs to determine the context in which words are being used, which helps determine the meaning. Ontology and semantic web-based search techniques provides capabilities to this direction. In ontology-based search, the search engine does not only understand hierarchical relationships of entities and concepts as in a taxonomy, but also more complex inter-entity relationships. Let us consider, for illustrative purposes, the question "What does a PV-system produce?" Ontology-based search would potentially bring up results about suppliers, energy, and houses, as they relate to PV-systems of course.

3.9 Ontology engineering methodologies

In the section on knowledge engineering, knowledge-based system development methodologies have been reviewed. Given that ontology development is a sub-task of a knowledge-based system, it is important to review and identify the ontology engineering methodologies that will be used in this study. Like in knowledge-based systems development, there are so many ontology engineering methodologies. The most commonly used ontology methodologies reviewed in this study are the Uschold and King Ontology Development Method (Uschold and King, 1995), Toronto Virtual Enterprise Method (Grüninger and Fox, 1995), Methontology (Fernández-López *et al.*, 1997), On-To-Knowledge (Staab *et al.*, 2001), Ontology Development 101 (Noy and McGuinness, 2001), and Horrocks Ontology Development Method (Breitman *et al.*, 2007).

3.9.1 Uschold and King ontology development method

Uschold and King (1995) proposed the first method for building ontologies, which was later on extended in Uschold and Grüninger (1996). They proposed guidelines based on their experience in developing the Enterprise Ontology. There are four major guidelines of constructing ontologies involved in this methodology. The sequential order of the guidelines is: identification of purpose and scope of the ontology, building the ontology, evaluation of the ontology and documentation of the ontology. The main drawback of this methodology is the lack of a well-defined conceptualisation process before implementation of the ontology (Gómez-Pérez *et al.*, 2004). Furthermore, no techniques have been suggested for performing the activities of the methodology such as how to identify the key concepts and relationships in a domain during the ontology capture stage (Pan, 2006). As a result this methodology was not adopted for the development of the sustainable building technology ontology presented in this study.

3.9.2 Toronto Virtual Enterprise method

This methodology emerged from Grüninger and Fox's (1995) experience in developing ontologies from business and corporate processes and was grounded on answering competency questions. The following are the major guidelines in the sequential order proposed by this methodology in the development of an ontology: description of motivating scenarios, formulation of informal competency questions, specification of ontology terms using a formal representation, formulation of formal competency questions, specification of axioms, and verification of the ontology's completeness. The drawback for this methodology is that the steps in this methodology are too vague and generic with no detailed techniques for undertaking the activities of the methodology. As a result it has not been adopted in this research.

3.9.3 Methontology

This methodology is for building ontologies either from scratch, re-using other ontologies or a combination of both (Antonio and van Harmelen, 2004). This could be done through ontology re-engineering processes. This methodology proposes in a sequential order eleven guidelines for developing ontologies.

- **Step one:** Planning: This first step involves the identification of all the activities to be undertaken;
- **Step two:** Specification: In this second step the scope and goals of the ontology are clearly spelt out;
- **Step three:** Conceptualisation: This stage entails the elicitation of the relevant concepts in the domain of the ontology;
- **Step four:** Formalisation: This stage consists of formalisation of the conceptual models in the previous stage;
- **Step five:** Integration: In this stage the ontology under development should be integrated with existing ontologies if available and if possible;
- **Step 6:** Implementation: This stage involves the writing or translation of this ontology into a machine-processable language such as OWL;
- **Step seven:** Evaluation: This entails the verification and validation of the ontology;
- **Step eight:** Documentation: This refers to the publication of the ontology in an appropriate media such as the Protégé ontology repository currently being hosted by Stanford Center for Biomedical Informatics Research at the Stanford University School of Medicine;

- **Step nine:** Maintenance: In order to avoid obsolescence, the ontology should be constantly maintained.

Compared with previous methodologies, the 9-step Methontology is the best in specifying ontologies from a knowledge engineering's point of view. Step four is about direct formalisation of conceptual models in the domain. In practice, this is possible with knowledge engineers who are quite conversant with the techniques of coding knowledge into formal languages. Novices will generally pass through intermediate stages, i.e. they will express knowledge as a set of intermediate representations before generating the ontology using an ontology design environment (Pan, 2006). Based on this argument, this methodology was not adopted.

3.9.4 On-To-Knowledge

This methodology was developed for the management of enterprise knowledge. The aim of the On-To-Knowledge project is to apply ontologiės to electronically manage available information for improving the quality of knowledge management in large and distributed organisations (Staab *et al.*, 2001). The steps in this methodology are:

Feasibility study: In an organisation, other than technology many other factors do influence its smooth functioning. This first step of the On-To-knowledge methodology aims to investigate and analyse these factors, for example, to identify problem/opportunity areas and potential solutions. In general, a feasibility study serves as a decision-support for economical, technical and project feasibility, determining the most promising focus areas and target solution.

Kickoff: This is the phase in which the actual ontology development process begins. In this phase the ontology requirements specification is established. The ontology requirements specification should establish what the ontology should support. It should also sketch the planned area of the ontology application. The ontology requirements specification should guide the ontology engineer to establish the concepts, relations and hierarchical structure to include and/or exclude in/from the ontology. One other activity at this stage is the semi-formal description of the ontology, i.e. a graph of named nodes with undirected edges both of which may be linked with further descriptive text. If the requirements specification is sufficiently captured, the ontology engineer can proceed to the next phase. The decision to proceed to the next phase is best taken when the ontology engineer must have sufficiently collaborated with domain experts. "Sufficient" here means domain experts are satisfied with the amount of knowledge captured and that there is no need to proceed in capturing and analysing new knowledge.

Refinement: The main aim of refinement is to obtain a mature and application-oriented "target ontology" according to the specification given in the kick-off phase. Two activities are often undertaken in this phase. The first activity is the knowledge elicitation process with domain experts. The baseline ontology, that is, the first draft of the ontology obtained in the kick-off, is refined by means of interaction with experts in the domain. When this activity is performed, axioms are defined and modelled. During the elicitation process, the concepts are gathered on one side and the terms to label the concepts on the other. The terms and the concepts are mapped. If there are several experts participating in the building of the ontology, it is necessary to reach an agreement. The second activity is the formalisation of the ontology. The ontology is implemented using an ontology language. The ontology language is selected according to the specific requirements of the envisaged applications.

Evaluation: The evaluation process serves as a proof of the usefulness of the developed ontologies and the associated software environment. The product obtained is called an ontology-based application. During this process two main activities are undertaken. The first is the checking of requirements and competency questions. The developers check whether the ontology satisfies the requirements and can answer the competency questions. The second activity is the testing or the evaluation of the ontology in the target application environment. Further refinement of the ontology can arise in this activity. The evaluation process is closely linked to the refinement process. In reality, several cycles are required until the target ontology reaches the envisaged level.

Application and evolution: In this last phase the application or usage of the ontology is described and documented. If there are future changes of the application then the ontology will have to be updated in order to meet up the changes in the application or usage of the ontology. This means ontologies undergo evolution over time. This evolution should be documented. The outcome of an evolution is an evolved ontology, i.e. typically another version of it.

The On-To-Knowledge methodology for building ontologies proposes to build the ontology taking into account how the ontology will be used in further application (Gómez-Pérez *et al.*, 2004). Consequently, ontologies developed with this methodology are highly dependent on the application. Therefore, this methodology will not be considered for use in this research.

3.9.5 Ontology development 101

This is a methodology designed to help beginners build their first ontology. The main guidelines in this methodology are the determination of the domain and scope of the ontology, consideration of re-using other ontologies, enumeration of important terms in the ontology, definition of classes and class hierarchy, definition of class properties, definition of facets of properties and creation of instances.

Step 1: Determination of the domain and scope of the ontology
Developing an ontology of a domain is not a goal in itself. As earlier defined, an ontology is a model of a particular domain, built for a particular purpose. What is included in the ontology is determined by the purpose of the ontology. To determine the domain of the ontology, competency questions are often asked (Noy and McGuinness, 2001). Competency questions are questions that provide guidance in defining the domain of an ontology. Also, competency questions provide clues about the scope of the ontology, what the required concepts that are required and those that are not required to be included in the ontology. Some examples are: What is the domain that the ontology will cover? How will the ontology be used? For what types of questions should the ontology provide answers? By finding answers to the competency questions, the domain of the ontology and its scope can be determined.

Step 2: Consideration of the re-use of other ontologies
Rather than inventing the wheel, it is almost always worth considering other existing ontologies and checking if they can be refined, extended or can be used in its entirety in a particular application. This is an important activity of ontology development

especially if the application to be built is required to interact with the applications that have already committed to particular existing ontologies.

Step 3: Enumeration of important terms in the ontology

This is the first step in actual definition of the ontology. It consists of writing down in an unstructured list of all the relevant terms that are expected to appear in the ontology. Typically, nouns form the basis for class names and verbs form the basis for property names. Traditional knowledge engineering tools such as laddering and grid-analysis can be productively used in this stage to obtain both the set of terms and an initial structure of these terms.

Step 4: Definition of the classes and the class hierarchy

After their identification, the terms are organised in a taxonomic hierarchy. Opinions differ on whether the top-down or bottom-up fashion should be adopted (Uschold and Grüninger, 1996). However, it is important to be consistent in the type of hierarchy chosen. This will also facilitate consistent reasoning in the ontology. As an example of a top-bottom hierarchy definition between two classes A and B; if a class A is a subclass of class B, then every instance of A is also an instance of B.

Step 5: Definition of the properties of classes

The classes alone will not provide sufficient information to attain the purpose of the ontology or answer the competency questions defined in Step 1. Therefore, in order to enrich the classes defined in step 4 the properties of classes are defined. Generally, there are three main types of properties widely acknowledged in the ontology community: the object property which defines the relationship between individuals of the various concepts, data-type property which defines the relationship between individuals and data-type values, and the annotation properties which provides more information about some key components of the ontology.

Step 6: Definition of the facets of properties

Facets are the different value types, allowed values and the number of the values (cardinality) describing a data-type property. For example, the different PV-system "module material types" is a string (value type), the different material types could be monocrystalline, polycrystalline and amorphous (allowed values) and the cardinality is 3 representing the total number of allowed values.

Step 7: Creation of instances

This step requires creating individual instances of classes which consist of: choosing a class, creating an individual instance of that class and filling in the property values.

3.9.6 Horrocks ontology development method

This is a simplified but very useful method for the development and editing of OWL ontologies (Breitman *et al.*, 2007). The methodology consists of two main guidelines.

The first guideline is about the determination of how the domain should work. This consists of the determination of classes and properties in the domain, the determination of the domains and ranges of properties, the determination of characteristics of classes, the addition of individuals and their relationships, and the refinement and iteration of the ontology until it is good enough. The second guideline is about building the OWL ontology. The consistency and coherency of the ontology should be verified. From a holistic point of view this methodology is very simplified compared to other methodologies reviewed in the preceding sections and more particularly it is a sub-methodology of the "Ontology development 101". Hence this methodology was not adopted in this study.

Having reviewed the most common ontology engineering methodologies, it is important to establish which methodology will be used in this thesis. Based on its explicit specification of the fundamental techniques and processes "Ontology development 101" (see section 3.9.5) was used in this research. Furthermore, its compatibility with protégé-OWL (a very popular ontology editor), was an additional motivational factor for its choice.

3.9.7 Ontology alignment/merging methodologies

Common to all the above ontology development methodologies is the fact that any ontology can be developed either from scratch or by re-using other ontologies if available and fulfil the requirements of the domain of discourse. Ontologies can be totally or partially re-used. The re-use activity is undertaken through adopting a whole ontology and extracting parts from another ontology. Upon adoption and extraction, these can be added, and compared with other ontologies in a process often termed *ontology alignment/merging.* The domain of ontology alignment/merging has recently attracted interest from the research community. This has led to the development of some alignment/merging methodologies such as the ONIONS, FCA_Merge and PROMPT well-reviewed by Gómez-Pérez *et al.* (2004). PROMPT (Noy and Musen, 2003) is the most popular of these methodologies and has a corresponding plug-in integrated into Protégé-OWL for the facilitation of ontology alignment/merging. Hence, PROMPT will be used in this study. One main advantage of using the PROMPT methodology is the fact that it semantically verifies the ontology developed without requiring the expertise from domain experts. Alignment/Merging ontologies entails comparing their components such as classes, instances, and properties and making appropriate choices on which components to include or reject from the final ontology. Considering the purpose of the use of the PROMPT methodology in this study, only the PROMPT operations dealing with the merging of classes in ontologies will be required and hence explained below. In PROMPT two key operations have been recommended in merging classes.

- Suppose a new class M is to be generated from the merging of classes A and B. If A and B have the same names, assign that name to M. Otherwise designate a name of choice and assign to M;

- If a superclass C of A or B has an image Ci in Om (merged ontology), make Ci a superclass of M.

The above two operations will be implemented in Chapter 6 for the development of the sustainable building technology and PV-system ontologies.

3.10 Ontology engineering editors

On reviewing popular ontology editors, it was found that most depend directly on ontology language and methodologies and this is reflected in the ease or difficulty in developing the ontology. Given that OWL has been chosen as the ontology language in this study, a suitable and compatible ontology editor is required. Accordingly, the following editors were reviewed: Karlsruhe Ontology (KAON) (Maedche *et al.*, 2003), OilEd (Bechhofer *et al.*, 2001), Ontolingua Server (Farquhar *et al.*, 1997), OntoSaurus (Swartout *et al.*, 1997), Web Ontology Design Environment (WebODE) (Arpírez *et al.*, 2003), WebOnto (Dominigue, 1998) and Protégé-OWL. After a critical comparison, Protégé-OWL was chosen because of the following reasons:

- Availability/accessibility: Protégé-OWL is a free software, and with a user-friendly interface. Furthermore, unlike many software, it contains detailed and concise ontology development guidelines often very useful for beginners;

- Flexibility: Protégé-OWL comes with so many plug-ins as extensions for different purpose; examples are OWLviz and Jambalaya for ontology visualisation and JessTab which allows the use of Jess (a rule language) and Protégé together;

- Easy integration: Protégé-OWL can be integrated with other software engineering tools. For example, Protégé-OWL can easily be run from most software integrated software development environments such as Netbeans and Eclipse. Also, Protégé-OWL can be integrated with most relational database management system (RDMS). OWL ontologies developed can be stored in MySQL as a back-end to enhance persistency;

- Time constraint: Compared to other tools such as Ontololingua, WebOnto, ProtegeWin, ODE, Ontosaurus (Duineveld *et al.*, 2000), Protégé can easily be learnt over a relatively short period of time even by those, like the author of this thesis with little or no background knowledge about the software engineering or computer science;

- Protégé-OWL contains a test framework, which can be run to check that ontology property's characteristics correspond with inverse property's characteristics. This test is executed through the use of a plug-in called "Run Ontology Tests" incorporated in Protégé-OWL;

- Compatibility with most syntax validators: Ontologies developed with Protégé-OWL can easily be checked for compliance with RDF or OWL syntax in RDF or OWL syntax validator. A common OWL syntax validator is OWL Ontology validator;

- Widespread usage: Currently Protégé is the best and the de-facto ontology editor (Lambrix 2003; Protégé Team 2009).

3.11 Evaluation of ontologies

With an increase in the use of ontologies in developing applications, the need to evaluate ontologies for use in respective applications is equally becoming increasingly important. Evaluation provides the basis upon which to judge the fitness of an ontology. Evaluation is a broad term that encompasses two terms including verification and validation (Kendal and Creen 2007; Bret *et al.* 2009). While *verification* mainly refers to technical activities that ensure syntactic correctness and cleanness of a knowledge base or an ontology (Kendal and Creen, 2007), *validation* refers to the process of ensuring that the ontology or knowledge base corresponds to the phenomenon that it is supposed to represent (Sommerville 2007; Al-Debei and Fitgerald 2009).

Like the various ontology definitions, an ontology evaluation is a term with different and often unclear and conflicting definitions. Kendal and Creen (2007) and Bret *et al.* (2009) consider ontology evaluation to mean ontology verification and validation. Guarino and Welty (2002) consider ontology evaluation to mean ontology validation. In order to adopt a definition for this study, it is necessary to remind ourselves of the ontology requirements. Why is the ontology being developed? What is the purpose of the ontology? Thus, ontology requirements provide guides to the choice of the evaluation technique. The definition of evaluation technique to mean verification and validation will be used. Verification will be used to establish the semantic and syntactic fitness while validation will be used to establish the intended purpose of the application ontology. The challenge is, how to semantically and syntactically verify the correctness of an ontology? Also how do we ensure that the ontology developed meets the intended requirements?

With regards to semantic verification, two main methods can be pursued depending on how the ontology was designed. If the ontology was developed from scratch, then consultation with domain experts to verify the concepts modelled in the ontology is often recommended. This is often time consuming and costly (Völker *et al.*, 2008). In the second approach, if the ontology is developed from the re-use of existing lightweight or heavyweight ontologies then depending on the degree of the re-used ontology the automated or manual alignment/merging semantic verification techniques can be used (Noy and Musen 2003; Gómez-Pérez 1994; Hovy 2001). In fact, the PROMPT technique of alignment/merging of ontologies semantically verifies ontologies by comparison (Noy and Musen, 2003). In these techniques, a given ontology is aligned to another ontology often referred to as a reference ontology or golden standard ontology (Gómez-Pérez 1994; Hovy 2001). For instance, ontology evaluation through alignment is described as an activity that given two arbitrary ontologies O1 and O2, aims to find for each concept in the ontology O1 a corresponding concept in ontology O2 that has the same intended meaning. By the latter methodology, if the re-used ontology has been adopted in its entirety, then there is no need in semantically verifying the ontology. On the other hand if it is partially re-used the new ontology components introduced needs to be semantically verified most preferably by domain experts and the re-used component by the alignment or comparison methodology.

After semantically verifying the ontology it is imperative to syntactically check the ontology's consistency. With respect to consistency checking, the developed ontology is checked against sub-sumption, equivalence, instantiation and consistencies (Antonio and van Harmelen, 2004). Syntactic verification is often conducted using reasoners such as Pellet 1.5.2 and (Fast Classification of Terminologies) FaCT++ which are plug-ins incorporated in Protégé-OWL. The use of reasoners eliminates anomalies in the ontology. In the literature, after syntactically verifying an ontology, it is advisable to verify the compliance of the ontology with the designed language. Is the ontology OWL or RDF compliant? Like in syntactic verification, there are semantic web tools for automatic verification of the ontology language compliance. For example, the Manchester OWL syntax validator is an OWL language compliant validator that accepts ontologies written in RDF/XML, OWL/XML, OWL Functional Syntax and Manchester OWL Syntax and checks if it is OWL compliant. If an ontology is not OWL compliant, then it will not support OWL reasoning techniques.

The semantic and syntactic verification of ontologies and the verification of language compliance prepare the ontology fit to be validated for the purpose for which it was developed. In the literature, case studies are often employed in establishing whether the developed ontology meets the ontology requirements or does what it was developed to do.

While it is important to develop ontologies, it is necessary to use the ontologies in developing semantic web applications. Most semantic web applications tend to use rule and/or query languages in outputting information required by end-users. Therefore, rule and query languages are important component of semantic web technologies. Since rules and queries are aimed at reasoning based on certain criteria, it will be necessary to first examine multi-criteria decision analysis - a decision technique based on many different criteria of objects.

3.12 Multi-criteria decision analysis

Selecting products and/or suppliers based on some constraints or criteria is a well-researched area known as multi-criteria decision theory (Herath and Plato 2006; Xia and Wu 2007; Goodwin and Wright 2009). Recently, multi-criteria decision-support systems have become common and have been developed and used in the selection of suppliers of given products. An intelligent supplier management tool has been developed to select and benchmark suppliers within the new product development process using case-based reasoning and neural network (Choy *et al.*, 2002). Using activity based costing with fuzzy data, Dogan and Sahin (2003) examined supplier selection problems under uncertainty conditions. A scoring method combined with fuzzy expert systems for supplier assessment in order to reduce human judgement errors was developed by Kwong *et al.* (2002). Data envelopment analysis has been developed as a tool for measuring the performance of suppliers on multiple criteria and for use in supplier negotiations (Weber, 1996). Masella and Rangone (2000) have proposed four different supplier selection systems based on time frame (long term and short term) and contents (logistic and strategic) of the co-operative supplier/customer relationships using analytic hierarchy process (AHP). Barbarosoğlu and Yazgaç (1997) presented the use of the AHP to deal with imprecision in supplier choice, which circumvents the difficulty of having to provide point estimates for criteria weights as well as performance scores in the basic linear weighting model.

Decision-making is a technique that models complex preferences about projects, products, services or anything that requires a choice to be made based on some criteria. However, the criteria on which to base judgements can often be conflicting. For example, a client who wants a highly efficient PV-system battery may be constrained by its high cost. These orthogonal ends of criteria upon which decisions are to be made is further exacerbated by considering many criteria. Traditionally conclusions established based on single criterion decision analysis are now too common. For instance, clients often use off-the-shelf prices in establishing decisions whether to buy a product or not.

However, single-criterion decision-making is very limited in dealing with real-life problems. As argued by Janikowski *et al.* (2000), using only a single-criterion is not considered the best approach. Furthermore, Janikowski *et al.* (2000) argue that it is very necessary for real-life problems to be addressed from a multi-criteria perspective. That is why many multi-criteria techniques have gained significant interest from the research and industry as a de-facto methodology for multi-criteria decision analysis. One suitable application of multi-criteria analysis is the area of sustainability. With the emerging sustainable global agenda, many businesses and governments are exploring multi-criteria decision analysis in appraising services and technologies for their sustainability performance.

3.13 Rule and query languages

As highlighted earlier, the main goal of the semantic web is to render information on the web that can be processed by both humans and machines. Web languages such as RDF Schema and OWL are limited in supporting the semantic web to achieve its dream.

These languages are designed to specify description of application domains. They offer constructs to describe classes, properties, and relationships, as well as constructs to capture class and property restrictions and to define complex classes (Alesso and Smith, 2009). Although ontologies provide the basis for some forms of reasoning, it is unlikely that ontologies, by themselves, will support the range of knowledge services that are likely to be required by the semantic web (Smart, 2007). Hence, in order to extend the reasoning capabilities of the semantic web so as to enhance automatic information processing, there is an urgent need to incorporate rules. So many rule languages exist with some notable ones being datalog, rule markup, web service modelling language, semantic web service language, TRIPLE and the semantic web rule language (SWRL). The SWRL has been chosen because of its ease of incorporation with other Protégé plug-ins.

3.13.1 Semantic web rule language

The limitation of OWL in providing deductive reasoning capabilities prompted the birth of SWRL (O'Connor *et al.* 2007; Horrocks *et al.* 2004). SWRL overcomes this deficiency of OWL by providing deductive reasoning capabilities that infer new knowledge from an OWL ontology knowledge base. SWRL is designed as a rule language for the semantic web and includes a high-level abstract syntax for Horn-like rules. Horn-like rules are a subset of predicate logic with efficient proof systems (Antoniou and van Harmelen, 2004). Like Horn-like rules, SWRL takes the form of an implication between an antecedent (body) and a consequent (head). The intended meaning is read as: whenever the conditions specified in the antecedent holds, then the conditions in the consequent must also hold. Symbolically the above statement is represented as:

Rule 3.1. Rule definition

$$A_1,\ldots A_{n-1}, A_n \rightarrow B \qquad \text{r-3.1}$$

where A_i and B are atomic formulas $\forall i \in \aleph$

Rule r-3.1 can be attributed two different interpretations. The two are deductive rules and the reactive rules. In the deductive rule, (r-3.1) is read as follows: if: $A_1,\ldots A_n$ are known to be true , then B is also true while in the reactive rules if the conditions $A_1,...A_n$ are true, then carry out B. Atoms can be of the form C(x), P(x,y), sameAs(x,y) differentFrom(x,y), or builtIn(r,x,...) where C is an OWL description or data range, P is an OWL property, r is a built-in relation, x and y are either variables, OWL individuals or OWL data values, as appropriate. In the context of OWL Lite, descriptions in atoms of the form C(x) may be restricted to class names (Horrocks *et al.*, 2004).

3.13.1.1 Reasoning using a SWRL language

Generally the kinds of inferences that can be performed on OWL knowledge bases are structural inferences such as subsumption and identity (Walton, 2007). This type of inference does not take into account the precise meaning of the information or semantics represented in the OWL knowledge base. In real life situations, it is always desirable to go beyond structural inferences which are not quite common with conventional database systems. To deal with this situation SWRL has been proposed to extend specifically OWL-Lite and OWL-DL with first-order-rules (Walton 2007; O'Connor *et al.* 2005; Horrocks *et al.* 2004). To facilitate editing SWRL rules, SWRLTab, an extension to the Protégé-OWL ontology development editor has been developed (O'Connor *et al.*, 2005). The SWRLTab plug-in has four main components: 1) an SWRL graphical editor, 2) a rule engine bridge, 3) a built-in bridge and 4) built-in libraries.

The SWRL graphical editor is an extension to the Protégé-OWL plug-in which permits the interactive editing of SWRL rules (O'Connor *et al.*, 2005). SWRL editor permits users to create, edit, read and write SWRL rules.

The rule engine bridge provides a bridge between the OWL knowledge, the SWRL rules and a third party rule engine or reasoner. Its goal is to provide the infrastructure necessary to incorporate rule engines into Protégé-OWL for executing SWRL rules. Furthermore, the bridge provides mechanisms to (1) import SWRL rules and OWL classes, individuals, properties and description from OWL ontology; (2) write the knowledge to a rule engine or reasoner; (3) allow the rule engine to perform inference and to assert its new knowledge back to the bridge and (4) insert the asserted knowledge into an OWL ontology.

The rule engine bridge also provides mechanisms to add graphical user interfaces to the SWRLTab to allow interaction between a particular rule engine implementation and users. The SWRLTab plug-in in Protégé facilitates the transformation from the ontology and rule based knowledge bases to the Jess engine. Once this transformation is complete, Jess execution engine can perform inference.

The SWRL built-in bridge provides a very powerful extension mechanism that allows the use of user-defined methods in rules. These methods are called built-ins and are predicates that accept one or more arguments. SWRL built-ins are user-defined predicates that can be used in SWRL rules. The SWRLTab has a subcomponent called the built-in bridge that provides a mechanism to define Java implementations of SWRL built-ins. These implementations can then be dynamically loaded by the bridge and invoked from a rule engine.

3.13.1.2 Querying using a semantic querying language

SWRL is a rule language and not a query language. Nonetheless, many ontology applications require the ability to extract information from ontologies in addition to reasoning with information in these ontologies. Ontologies querying languages such as RDQL, (New Racer Query Language) nRQL and SPARQL have been developed to facilitate the extraction of information from ontologies. Among these ontology query languages, SPARQL is the most advanced with respect to extracting information from OWL. While SPARQL and its extensions are being used as an OWL querying language in many applications, their understanding of OWL's semantics is at best incomplete (O'Connor and Das, 2009). To address this shortcoming of SPARQL, a concise, readable and semantically robust query language SQWRL (Semantic **Q**uery-**E**nhanced **W**eb **R**ule **L**anguage; pronounced squirrel) for OWL was developed by O'Connor and Das (2009). SQWRL takes a standard SWRL rule antecedent and effectively treats it as a pattern specification for a query. It replaces the consequent with a retrieval function. This function is often denoted as *sqwrl:select.* It provides Structured Query Language (SQL)-like operations to retrieve knowledge from OWL. The SQWRLQueryTab is a plug-in in Protégé-OWL that provides a graphical interface to work with SQWRL queries. It provides a convenient way to visualize the results of queries on OWL ontology. This will be exploited in this study.

3.13.2 Simple Protocol and RDF query language (SPARQL)

SPARQL defines both a network protocol for the exchange of queries, and a language for expressiing queries. SPARQL adopts an SQL-like syntax for expressing queries, rather than an XML-based syntax (W3C, 2008). The motivation for the development of SPARQL is an attempt by the W3C to replace a large number of existing RDF query languages such as RQL, RDQL and RDF query with a common standard (W3C, 2008). RQL is still the only declarative language for querying both explicitly stated triples of RDF/S graphs and inferred ones by transitivity of sub-sumption and type relationships. RDQL is a query language for RDF in Jena models. Jena is a programmatic Java framework for building semantic web applications (Jena, 2010). In the Jena world, the corresponding interfaces are called Graph and Model hence the name Jena model (Protégé-Jena, 2010).

3.14 Semantic web browsers

In the previous sections, the examination of ontology languages, tools and rules have been undertaken. However, the majority of users that will use ontological knowledge bases are not ontology engineers or even computer literates. There is need therefore to provide platforms or user interfaces that can be used in browsing and exploring ontologies in a semantic web environment. Although research towards developing semantic web browsers is still in its infancy, some very light weight ontology browsers do exist. These are the Protégé web browser, OWLSight and the OWL Ontology-browser.

The *Protégé web browser* is a java-based web application that allows the user to share, browse, and do some basic editing of Protégé knowledge bases via the WWW (Ahsan, 2010).

The *OwlSight* is an OWL ontology browser that runs in any modern web browser. It is developed with Google Web Toolkit and uses Gwt-Ext, as well as Web ontology language-Application Programming Interface (OWL-API). The browser is been developed by Clark and Parsia; one of the leading suppliers of innovative semantic web technologies, with a particular focus on OWL automated reasoning (PL, 2010). OwlSight is the client component and uses Pellet as its OWL reasoner (PL, 2010).

The *OWL ontology-browser* provides the means to navigate around ontologies in the same familiar environment, but produces the pages dynamically and is available for direct use with a web front-end (OB, 2010).

3.15 Overview of semantic web system architecture

Presently, the domain of information technology has been over-flooded with thousands of tools, techniques, programming languages, etc. for application developments. Unfortunately, there is hardly a document that harnesses a group of any of the technologies for a particular application development (Turner, 2002). This is a major problem to application developers as too much time is spent in assembling and installing the required technologies as a composite system so that they can effectively interoperate with each other. Nonetheless, currently in the field of information systems, current web and database management systems, there has been a significant progress towards integrating most isolated software. As an example, WAMPServer is an integrated tool suite made up of Apache, MySQL and PHP commonly used for web development (WS, 2010). Being an emerging technology, the semantic web still suffers from the lack of integrated software that can be used in developing efficient semantic web systems in a shorter time. In software engineering the task of rendering information to an end-user through the implementation of any computer system often involves three separate processes: the presentation, the application processing and data management processes. This is often called the hybrid system, client-server architecture or 3-tier architecture. Access to the presentation layer is often through the use of a graphical user interface (GUI) or a web browser. As presented by Alonso *et al.* (2003), the implementation of the 3-tier model in its full generality and the invocation of access via the internet or web browser is called an N-tier model. Thus, implementing an N-tier model in the design of semantic web application provides insightful knowledge into the types of semantic web technologies involved. In Figure 3.5, an N-tier architecture is presented.

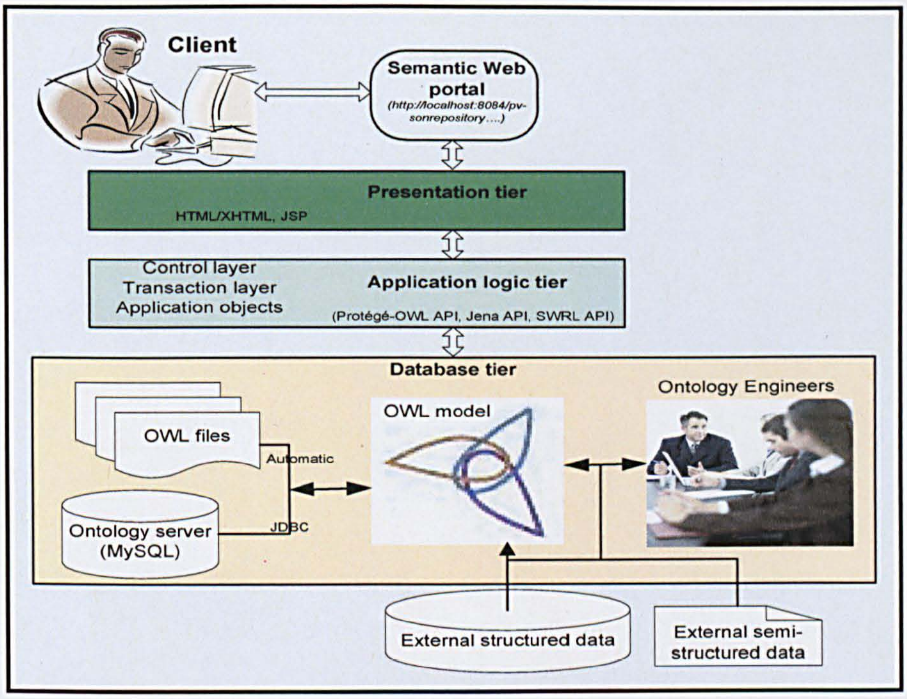

Figure 3.5. The semantic web N-tier architecture

The main components of the system to be developed in an N-tier architecture are the clients or web browser (i.e. the terminal that enables end-users to acquire information otherwise known as the web browser or GUI application), the presentation tier responsible for communicating with external entities such as humans and/or machines, the application tier (responsible for the programming logic) and the database tier (responsible for housing data and transferring it to the application tier). The database tier communicates with the external entities by extracting information from humans or machines. The N-tier model based on a 3-tier architecture is an emerging and fast becoming the de-facto standard for scalable web applications (Svend and Rachid 2002; Chiu *et al.* 2003; Halfawy and Froese 2007). Furthermore, the advantages of N-tier architecture are: adaptability, encapsulation, re-use and quality. With regards to adaptability it is easier to modify or replace any of the tiers without affecting any of the other tiers.

The relationships between the different web technologies, Java technologies, software with regards to the N-tier architecture is shown in the Table 3.4.

Table 3.4. Relationship between semantic web technologies in the 3-tiers

Tier	Web & Java technologies	Software
Presentation	XHTML, CSS, XML, XSL, Javascript	XML enabled web browser Apache Web Server
Application	JSP, JavaBean, Server-side Java class	J2SE, tomcat JSP server, Protégé-OWL API, JENA API
Data access and storage	JDBC	MySQL DBMS Protégé-OWL, OWL files

[CSS: Cascading Style Sheets, XHTML: eXtensible HyperText Markup Language, XSL: Extensible Stylesheet Language, JSP: JavaServer Pages, J2SE: Java 2 Platform, Standard Edition, DBMS: Database Management System, JDBC: Java Database Connectivity]

3.15.1 The Presentation tier

This tier deals with programs that handle all operations between the end-users and the client browser. It contains all the operations that are visible to the end-user, such as the screen layout and navigation processes. Principally, it contains all the logic for accepting input from end-users and displaying the results as output. Consequently, it is often referred to as the graphical user interface or web browser. Following the 3-tier model, this tier communicates directly with the application tier through which an end-user is able to send a request to the application tier and also able to navigate both the static and dynamic web pages generated on the server side. In this tier JSP and HTML pages are often used in shaping the prototype graphical user interface. Furthermore, servlets are often employed in managing end-users' input and output data. With increasing importance of the semantic web, recent development indicates that some studies have been conducted in the development of semantic web browsers. Semantic web browsers are technologies that facilitate the browsing of ontologies over the web. Most of these semantic browsers are developed using the JSP, HTML–like technologies. An example of a web browser is OWLSight.

3.15.2 The application tier

This tier is the core of the model. It is the tier that links both the presentation and database server tier. The two main functions of the application tier are the enabling the connection to databases and the role it plays as a centralized repository of business logic. This tier is responsible for the processing of data before the results are ready to be delivered to the presentation layer. The application tier exposes the services offered by the semantic web portal. In this tier the following are undertaken: servlets or Java classes are responsible for coding the business logic and in charge of the access to data storage.

3.15.3 The database tier

This layer consists of the database management system and the database itself. This database management layer manages the storage, retrieval of data as well as allows simultaneous access, provides security, data integrity and support applications.

3.16 Prototype development

The term *prototyping* is an iterative process of developing an experimental system that is not intended for deployment by the customer (Sommerville, 2007). A prototype is an initial version of a system that is used to demonstrate concepts, try out design options and, generally, to find out more about the problem of a system and its possible solutions (Sommerville, 2007). Prototypes exhibit the essential features of a later operational system. Some prototypes may evolve into the actual system whereas others are used only for experimentation and may eventually be replaced by the system (Fitzgerald *et al.*, 2002). Prototyping can be used at any stage of a knowledge model construction phase. The application of prototyping at any stage of construction of a knowledge model makes it a suitable methodology for knowledge-based systems including ontology knowledge bases. Particularly with regards to ontology knowledge bases, prototypying is important because in the very early stages on ontology development, requirement specifications - an important aspect of ontology development is hardly completely elicited. Despite the fact that the requirement specification is hardly captured in one goal, the ontology engineer however proceeds to subsequent stages and when new facts emerge, the facts are introduced as requirements and the subsequent steps continue in a cyclic fashion. Moreover, the fact that syntactic and semantic errors are almost inevitable in the ontology development process, continually refining and re-building the system is very imperative until a robust structured prototype is obtained. This is often called evolutionary prototyping.

3.17 Decision choices on the different semantic web technologies

Although some main ontology methodologies, tools and langauages (see sections 3.9, 3.10 and 3.13) are required for the development of semantic web knowledge-based systems, some associated techniques and technologies including plug-ins are often required to efficiently implement them. The importance of these associated techniques and technologies have gained ground in the semantic web community and comparative studies about their use have been reviewed in Corcho *et al.* (2003), Antonio and Harmelen (2004) and Gómez-Pérez *et al.* (2004). As a result, this work will not be duplicated in this study. Rather, only the appropriate techniques and technologies necessary for the purposes of this study will be presented (see Table 3.5).

Table 3.5. Choices of semantic web technologies

Semantic web technology	Choice	Justification
Ontology languages	OWL-DL	Highly expressive
Ontology editors	Protégé-OWL 3.4.4	Very easy to use, very extensible, contain so many plug-ins
Knowledge engineering methodologies	CommonKADS	De-facto industry tool
Ontology engineering methodologies	Guide to Ontology Development 101	Easy to use
Evaluation methodology	PROMPT	Exists as a plug-in in Protégé-OWL and easy to use in semantically verifying ontologies
Rule language	SWRL	The most popular semantic web languages with readily available technical support
Query language	SQWRL	More powerful than other semantic web query languages and builds on SWRL
Query and rule editor	SWRLTab	The only plug-in for editing SWRL rules and SQWRL queries in Protégé-OWL.
Rule engine	Jess	A popular rule engine for reasoning over knowledge bases. Its powerful scripting language that enhances access to all of Java's APIs
Rule engine bridge	JessTab	The only plug-in for the

		Protégé-OWL that allows the use of Jess and Protégé together
Reasoner for syntactic validation	Pellet 1.5.2	An OWL reasoner embedded in Protégé-OWL 3.4.4
OWL language compliance validation		An OWL compliance developed by the School of Computer Science, Manchester University and is very reliable
Visualisation tool	Jambalaya	Very flexible and exists as a plug-in which can be easily incorporated into Protégé-OWL 3.4.4
Scale of system	Prototypes	Iterative processes best executed by using evolutionary prototyping suitable for developing ontologies
Semantic web architecture	Database & application tier	The development of a web interface is out of scope of this study

3.18 Conclusion

The chapter has explored current web technologies. A gap analysis was undertaken where weaknesses were discovered, as well as its inability to provide mechanisms that can enhance reasoning in knowledge-based systems. This formed a basis for the exploration of an emerging semantic web technology which culminated into two main outcomes - the establishment of the rationale for investigating the use of semantic web technologies in modelling knowledge about sustainable building technology domain and the identification of key semantic web technologies. Although it is not feasible to identify and discuss in detail all the semantic web technologies, a summarised list was presented in Table 3.5 to provide an overview of these technologies. The identified semantic web technologies can be used in different ways towards the development of semantic web applications. Consequently, it is not so straightforward to establish the level of specificities of usage of these technologies. One of the ways of establishing the specificities of applications of the semantic web technologies can be through the examination of how semantic web technologies have been applied to different domains. This is a matter dealt with in Chapter 4.

4. SEMANTIC WEB TECHNOLOGIES APPLIED TO BUILDINGS

4.1 General

Having explored in Chapter 3 the semantic web domain, this chapter goes a step further to establish how semantic web technologies have been experimented with developing real-life or prototypical applications. This is important in order to establish the extent to which semantic web technologies have been employed in other areas including the construction domain and particularly to the sustainable building technology domain. Although the establishment of the extent of use of semantic web technologies is the main objective of this chapter, the identification of other suitable ontologies for re-use in applications to be developed in this thesis is equally very important. The second section of this chapter is the background. It provides an overview of the extent to which semantic web technologies have been embraced by different organisations. In section 4.3, a holistic approach is undertaken in examining the applications of semantic web technologies to enterprise knowledge management, e-learning and building construction. In section 4.4, an overview of semantic web applications in the sustainable building technology domain is presented. In section 4.5, a critical analysis of the different semantic web applications to construction and sustainable building technology is undertaken. The chapter concludes by a way of discussion and summary establishing why there is need for a sustainable building technology semantic web system.

4.2 Background

The rapid advances in information and communication technology have given many industries including the construction industry opportunities to enhance business processes and maximize profits. Currently research is being undertaken by different business organizations in finding the best information and communication technologies necessary for use in their various information departments. It is increasingly becoming evident that research institutes and businesses are now shifting their research interest towards advanced communication technologies for implementation in different application domains. The nascent semantic web technology is crucial in the advancement of information and communication technology. The promises and opportunities from semantic web technology and its founders have sparked a global race towards the implementation of these technologies in businesses.

Multinationals such as Google, Yahoo and Microsoft are examples of large organisations that have recently embraced the semantic web in enhancing their search capabilities (Google 2009; Microsoft 2009; Yahoo 2008). Though the construction industry lacks motivation in terms of embracing innovative technologies including communication technologies (Egbu *et al.* 2001; Egbu and Botterill 2002; Brewer and Gajendran 2009; Pan *et al.* 2007); desk studies reveal that different kinds of advanced computer science techniques or parts of artificial intelligence commonly used in semantic web technology have been applied in the domain of construction (Kauffman *et al.* 2008; Zhiliang *et al.* 2005; van Truong Luu *et al.* 2009; Zhiliang 2009). Artificial intelligence techniques applied are case-based reasoning, fuzzy logic, neural networks, Bayesian networks and rule-based reasoning. These techniques have been applied to key areas of construction such as supply chain management, decision-support systems, cost optimisation, project, risk and construction management, etc. (Kauffman *et al.* 2008; Zhiliang *et al.* 2005; van Truong Luu *et al.* 2009; Zhiliang 2009). Other than the core artificial intelligence techniques, artificial intelligence application areas such as electronic construction information have recently been gaining ground with significant shifts towards semantic web technologies (Aziz *et al.* 2004; Chassiakos and Sakellaropoulos 2008; Rees 2006; Pan 2006). Recently, it has been argued in Smart2020 (2008) and Roeller *et al.* (2001) that with the gloomy world economy and the challenges posed by the impacts of climate change, information and communication technology with semantic web as the backbone is likely to be a key technology to be used in mitigating the impacts of climate change. Information and communication technology can provide data which can be used to change behaviours, processes, capabilities and systems in so many domains (Smart2020, 2008). Semantic web technology offers many opportunities and substantial capabilities to this direction (Chassiakos and Sakellaropoulos, 2008).

To appreciate the capabilities of the semantic web and the opportunities that can be reaped, it is important to examine the areas where the semantic web has been applied, as well as how the semantic web has been applied in the different sectors including the building construction sector. Furthermore, it is important to explore the future trend of semantic web applications. These will be examined in the ensuing section.

4.3 Semantic web applications

The purpose of this section is to review existing semantic web applications and to establish the extent to which these applications have been successful or unsuccessful in providing real solutions to real problems that cannot be solved by current web technologies. This will serve as a stimulus to applying semantic web applications to the domain of sustainable building technologies. While the semantic web has been gaining ground in the research community and the industry, there has been a surge in the research about their applications in the different domain. However, because the semantic web itself is still emerging, it has been difficult to establish a general trend, characteristics, and exact level of maturity of the different semantic web applications. It is very challenging to establish which applications are prototypes or real applications, who is using them and how they are being used. Nonetheless, after a thorough literature review four application areas of the semantic web were identified. These are enterprise knowledge management, e-learning, building construction and the sustainable building construction technology domains. The reasons for these choices are examined in the ensuing paragraphs.

Firstly, in order to have an overview of how the semantic web has been applied in other fields, enterprise knowledge management example was chosen. In particular, the example is about knowledge management in a very large company, the SwissLife Group. This was because SwissLife has been used as a case study in the implementation On-To-Knowledge, an established ontology engineering methodology. Furthermore, information about the application of semantic web on knowledge management in the SwissLife Group was readily available.

Secondly, based on the overall application trends of the semantic web, a potential future realistic scenario was chosen. This is e-learning as it is one of the areas already gaining significant attention within the semantic web community in which different sectors have expressed interest.

Thirdly, a realistic scenario which has been implemented in the domain of construction has also been considered. In this case, the e-COGNOS project was used as an example. Also in this category a brief review of other semantic web applications in the domain of construction are examined before focusing on the e-COGNOS project. This was to have an overview of the type of semantic web applications already in existence in the construction domain.

Lastly, it was also necessary to investigate whether some semantic web applications exist in the sustainable building technology domain. While it is important to know the different semantic web applications in the sustainable building technology domain, it is more important to know the different available building construction ontologies as it could lead to the identification of possible components for re-use.

4.3.1 Enterprise knowledge management

Qualities such as tacit knowledge, personal competencies and skills of employees are the most important resources of an enterprise for solving knowledge intensive tasks such as problem-solving, decision-making and strategic planning. These qualities are the most important assets that determine the real success of an enterprise (Taubner and Brössler 2000; Grant 1996a; Grant 1996b). Establishing electronically accessible repositories of the afore-mentioned qualities is key in setting up enterprise knowledge management (Reich *et al.*, 2002). Such a repository can be used to search for people with specific skills, reveal skill gaps and competency levels, direct training as part of professional development and document the company's intellectual capital. In the ensuing paragraphs, two real-life cases where the semantic web has been applied for enterprise knowledge management are examined. These are the SwissLife Group and the TOronto Virtual Enterprise (TOVE) projects.

SwissLife is a leading life and pension provider in Switzerland and it is one of the top ten insurance providers in Europe. As of the end of 2009, SwissLife employed about 8200 staff (SwissLife, 2010). The company has subsidiaries, branches, representative offices and partners representing its interest in so many countries including Germany, France, Dubai and Singapore (SwissLife, 2010).

The challenge is, with such a large multinational enterprise with a large international workforce distributed over many geographically and culturally diverse regions, the design of a world wide skill repository is a daunting task. Specifically, some of the challenges are how to list the large number of different skills? How to organise them so that they can be retrieved across geographical and cultural boundaries? How to ensure that the repository is updated frequently?

To address the above challenges, SwissLife was employed as a case study in the implementation of the On-To-knowledge ontology development methodology (Lau and Sure 2002; Antonio and van Harmelen 2004). Using SwissLife as a case study, a hand-built ontology to cover skills in three organisational units of SwissLife: (Information Technology, Private Insurance and Human Resources) was developed. Across these three sections, the ontology consisted of 700 concepts, with an additional 180 educational concepts and 130 job function concepts that were not sub-divided across the three sub-domains (Antonio and van Harmelen, 2004).

Individuals within SwissLife were asked to create "home pages" based on form filling that was driven by the skills ontology. The corresponding collection of instances could be queried using a form-based interface that generated RQL queries. Although the system never left the prototype stage, it was in use by initially 100 people (later 150 people) in selected departments of SwissLife at its headquarters (Antonio and van Harmelen, 2004).

Another major enterprise knowledge management project is the TOVE ontology project. The TOVE project developed a set of integrated ontologies for the modelling of both commercial and public enterprises. The main focus of the TOVE project is to promote enterprise integration, i.e. improve communication and coordination within and between organizations in order to achieve higher levels of productivity, flexibility and quality. The main ontologies that emerged from this project are the activity, resource, organisation, product requirements, ISO9000 quality and activity-based costing ontology.

4.3.2 E-learning

The advent of the web has prompted changes in the way things are done. In the education sector, for example, there is now e-learning, where learning is implemented by many institutions. Traditionally, e-learning has been characterised by the following properties:

- Educator-driven: The instructor selects the content and the pedagogical means of delivery, and sets the agenda and the pace of learning;

- Linear access: Knowledge is taught in a predetermined order. The learner is not supposed to deviate from this order by selecting pieces of particular interest;

- Time and locality-dependent: Learning takes place at specific times and specific places.

Consequently, learning has not been personalised but aimed at mass participation. Though efficient and in many instances effective, traditional learning processes have not been suitable for every potential learner. The emergence of the internet has paved way for implementing new educational processes. The changes are already visible in higher education with increase in the number of virtual universities and many online courses quite visible. E-learning is characterised by a greater flexibility than the traditional learning, where although students' presence on campus are still required, in the e-learning the students are subjected to fewer constraints. Increasingly, students can make more choices; determine the content and evaluation procedures, the pace of their learning and the learning method most appropriate and suitable for them.

In particular, e-learners can access material in an order not pre-defined, and can compose individual courses by selecting educational material. An example is a case where instead of a learner browsing through subjects like chemistry, physics and biochemistry to find out if these subjects deal with thermodynamics, the learner can instead decide to search for thermodynamics with the aim of finding its related subjects. For this type of query to work, learning materials or subjects must be equipped with additional information to support effective indexing and retrieval (Antonio and van Harmelen, 2004). Although standards for learning object metadata such as Institute of Electrical and Electronics Engineers Learning Object Metadata (IEEE LOM) have emerged (Kraan and Barker 2005; Ouafia *et al.* 2008), to provide effective indexing and retrieval by associating learning materials information such as educational and pedagogical properties, access rights and conditions of use, they suffer from a common drawback associated with current web technologies. This is because these standards adopt solutions based on solely metadata, XML-like approaches which lack the semantics to be exploited by machines. This translates to students not optimally exploiting the rich knowledge materials on the web. By introducing the semantic web technologies, a common shared meaning - an ontology can be made understood by computers which is the core of the semantic web. By developing ontologies about learning objects, semantic query and conceptual navigation of learning materials can be supported. Hence, the following benefits can be achieved:

- Learning materials could be connected through ontologies possibly under concepts such as "by authors", "by subjects" or even "across subjects". This can greatly facilitate information retrieval with a high degree of independence on the part of the students who can obtain information whenever required. This mode is now shifting from educator-driven to learner-driven;

- Greater flexibility in accessing knowledge: With ontologies as the backbone of knowledge bases over the web, the order of accessing information over the web becomes immaterial. Learners will access information without any constraints;

- Integration: The semantic web can provide a uniform platform for business process of organisations, and learning activities can be integrated in these processes. This solution may be particularly valuable for commercial companies, which may be interested in identifying and establishing if learning materials address their needs. This can lead to recommendations and collaboration between universities and companies on learning objects to be offered.

4.3.3 Semantic web applications applied to building construction

In the construction domain, the semantic web has been explored in the field of construction education, supply chain, project and construction management, material storage, project design, architecture and graphic designs, etc.

In the field of construction education, repositories have been developed in managing objects as well as metadata using ontologies that offer a set of services such as storing, retrieving and searching of learning objects using semantic web technologies (Ahmed *et al.* 2007; Pathmeswaran and Ahmed 2009; Argüello *et al.* 2006a; Argüello *et al.* 2006b). In the domain of supply chain, great use of semantic repositories about information from different partners on a common or different projects have been undertaken (Zou and Seo 2006; eBuild-XML 2001). In construction and project management semantic web repositories have been developed to enhance interoperability over computer systems to facilitate different companies'construction projects' information (Aziz *et al.* 2004; El-Diraby *et al.* 2005; Ruikar *et al.* 2007; Shelbourn *et al.* 2006; Owolabi *et al.* 2006; Ping Chen *et al.* 2005). Furthermore, integrated management and accounting systems for general and engineering contractors and sub-contractors of all trades for real-time construction management system have been developed using the semantic web technologies (MB7, 2000). In the material technology domain, XML technologies have been developed for interchange of materials information. It addresses the problems of interpretation and interoperability for materials property data exchanged via the WWW (MatML, 2003). In project design, information generated from the pre-planning stage can be processed and retained in the format which all the project participants can share. This has been achieved using object-oriented attributes and meta-data in Building Information Modelling and implemented in OWL ontologies (Lee *et al.*, 2008). In architecture and graphic designs, standards have been developed by the International Alliance for Interoperability for data representation and file format (i.e. Industry Foundation Classes XML (ifcXML)) for defining architectural and constructional CAD graphic data based on XML technologies. This aims at facilitating the transfer of design data by architectural CAD to and fro between rival products (IAI, 2006 cited in Pan, 2006). Similar projects based on XML technologies such as building and construction eXtensible Mark-up Language (bcXML) (Tolman *et al.*, 2001) and Architectural, Engineering and Construction XML (aecXML) (IAI, 2002 cited in Pan,

2006) have been used in establishing meta-data-based collaboration system model in order to substitute web-based collaboration in construction project management (Leung *et al.*, 2003). Lima *et al.* (2003), Lima *et al.* (2005) and Wetherill *et al.* (2002) have proposed a high level generic ontology (e-COGNOS project) for interoperation between the knowledge bases of construction enterprises. El-Diraby and Kashif (2005) investigated the use of distributed ontology architecture for knowledge management in highway construction. This architecture linked utility to highway geometry and served as a base for a cross-discipline knowledge exchange in the infrastructure domain. It was developed as an extension for the e-COGNOS ontology. Teller *et al.* (2009) and Teller *et al.* (2005) have investigated how ontologies work in practice to inform the development of future ontologies and conceptual tools that will make communication between urban development disciplines easier. In Beetz *et al.* (2009), an OWL ontology called ifcOWL was derived from the EXPRESS schema of the Industry Foundation Classes (IFC) version 2x2. The IFC data model is a neutral and open specification, an object-oriented file format with a data model developed by buildingSMART (International Alliance for Interoperability(IAI)) to facilitate interoperability in the building industry, and is a commonly used format for Building Information Modeling (BIM). EXPRESS is a standard data modeling language for product data (Beetz *et al.*, 2009). Another IFC compliant information model is CityGML (Kolbe *et al.*, 2005). While the IFC model describes project information such as building elements, geometry and material properties, costs, schedules, and organizations (Wang *et al.* 2007; Cerovsek 2010), CityGML defines the geometry, topologies, appearance, and semantics of urban objects including buildings for modeling and exchanging virtual 3D city models to support such applications as urban planning and simulation, facility management, and disaster management (Kolbe *et al.*, 2005). Although IFC and CityGML both model information about buildings, they 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 (Thurston, 2008). Like CityGML that has re-used the IFC building concept (Thurston, 2008), some IFC building properties will be abstracted and used in this study.

Of all the above semantic applications, e-COGNOS is the most notable. E-COGNOS was born out of the numerous projects' information and knowledge management problems plaguing the construction industry across Europe. These problems have been acknowledged by practitioners and researchers in Europe as major challenges in the 21st century. These problems have been examined by Rezgui (2001) and a summary is presented below:

- Construction information resides in the minds of construction professionals working on a given project;

- Discussions between project partners during construction processes are often not documented. This is due to the fact that each construction project is unique involving complex processes, thus very challenging to keep a record of messages, phone calls, memos and postal letters which constitute a greater bulk of project-related information;

- The collection of construction data may occur at different stages of the construction life cycle. Those who collect and archive the data may not know the needs of those who will use the data in future (such as professionals involved in the maintenance of buildings);

- Generally, data collected during construction processes are not managed until at the end of the construction stage. However, those who might have participated in the project and possess knowledge about the project might have left the project and their input is often not captured;

- From a project management's perspective, lessons learnt are not well organised and buried in too much unnecessary details. Consequently, it is difficult to compile and disseminate useful knowledge to other projects;

- Many construction firms archived historical reports of projects. Given that the construction industry is plagued with a high level of mobility of professionals between different firms, it is often challenging if not impossible to reach the authors of historical report who understands the hidden meaning of the project data in the report.

Based on the above problems technical experts working for major contractors in Germany, Finland and the United Kingdom (UK), and the project partners decided there was a need for new web-based software. To this end, E-COGNOS, a web-based software that integrates three distinct areas of knowledge in the construction domain was developed (Rezgui, 2001). The three areas of knowledge are:

- Domain knowledge: This includes administrative information such as zoning regulations and planning permission, standards, technical rules and product databases, etc. In practice, this information is available to all companies and is partly stored in public electronic databases;

- Organisational knowledge: This is knowledge that does not only limit to documents or repositories but also include organisational routines, processes and practices;

- Project knowledge: This is the potential for usable knowledge and is at the heart of much of the knowledge identified above. It is both knowledge each company has about the project and the knowledge that is created by the interaction between firms. It is not held in a format that promotes re-use, thus companies and partnerships are generally unable to capitalise on this potential for creating knowledge.

As noted by a project leader Giraud-Carrier in Flöck (2005): "Many companies already have various components to manage knowledge in this field (i.e. construction). They rely on intranets, e-learning and so on. But because these components develop over time and separately, interoperability with other systems is often lacking."

Thus, the output of the e-COGNOS project was an open-source software, mainly Java-based, to capture knowledge made up of three main components. These components have been reviewed in Flöck (2005) and include:

- Ontology in DAML+OIL format: This ontology consists of 15,000 English language construction terms. These terms have been developed from an existing thesaurus and terms provided by project partners. The ontology has been classified into seven major knowledge domains. These are the project, actor, resource, product, process, technical topics (conditions), and related domains (work environment). These break down into sub-sections, such as materials, labour force, equipment, and subcontractors under the banner of "resource";

- An ontology server (e-COSer): This provides the functionalities required to make the selected ontology available to the other e-COGNOS services;

- A Knowledge Management Infrastructure (e-CKMI): This infrastructure automatically extracts meaningful knowledge from documents, using text analysis and ontology techniques.

However, e-COGNOS was intended to resolve the information inconsistency problem in sharing knowledge bases between companies. Consequently, it did not take advantage of some of the key semantic web techniques such as rules that provides capabilities of overcoming information inconsistency (Pan, 2006).

4.4. Semantic web applications applied to sustainable building technologies

To appraise the extent to which semantic web has been applied in the sustainable building technology domain, an extensive literature search was undertaken. One of the key findings of the review was that there was no real significant application of the semantic web to sustainable building technologies. The few studies with at least some sustainability issues in the built environment are in Macris and Georgakellos (2006) and Edum-Fotwe and Price (2009). Macris and Georgakellos (2006) explored the use of ontologies to help students to understand the contemporary global environmental issues, how they are linked and interrelated and to consider the different views of these issues, before reaching a decision or judgment. Edum-Fotwe and Price (2009), on the other hand, explored the use of ontologies in appraising sustainability of construction projects and development from the social component of sustainable development. The ontologies developed by Macris and Georgakellos (2006) and Edum-Fotwe and Price (2009) are nothing more than academic papers and have never gone beyond prototypical system levels. However, this is not surprising given that the semantic web technology is still emerging and thus most applications in this domain are still very exploratory.

Nonetheless, it emerged that there is abundance of green/sustainability specifications/standards/ratings/metrics in the literature dealing with various aspects of sustainable constructions. Some examples of these specifications are the Market Transformation Programme database that contains the different building household appliances in the UK houses arranged in a well-defined taxonomy (Market Transformation Programme 2010; Firth *et al.* 2008; Wood and Newborough 2007), the Green Guide to Specifications (Anderson and Shiers, 2009), the Uniclass (Smith *et al.*, 1997) and the Leadership in Energy & Environmental Design (LEED, 2011). The Green Guide aims to provide a simple green guide to the environmental impacts of building materials which is easy-to-use and soundly based on numerical data. Uniclass is a recent classification scheme for the construction industry (Smith *et al.*, 1997). It is intended for organising library materials and for structuring product literature and project information. It incorporates both CAWS (Common Arrangement of Work Sections for building works) and EPIC (Electronic Product Information Co-operation), a new system for structuring product data and product literature. The Green Guide is part of BREEAM (BRE Environmental Assessment Method) an accredited environmental rating scheme for buildings. LEED is an internationally recognized green building certification system developed by the United States (US) Green Building Council, providing third-party verification that a building or community was designed and built using strategies intended to improve performance in metrics such as energy savings, water efficiency, CO_2 emissions reduction, improved indoor environmental quality, and stewardship of resources and sensitivity to their impacts. As these specifications have been developed by different individuals or agencies they tend to overlap, and often it is difficult to establish the detailed content of a specification and the challenge they address. Of recent there have been discussions in the research community on how to find ways of harmonising these specifications through the use of software to facilitate interoperability. Currently the "Green-Sustainability Specifications Knowledge base" is developing web-based front-end based on ontologies developed in XML, RDF, and OWL. The Green-Sustainability Specifications knowledge base will aim to contain all known regulations and standards in green and sustainability space. Although achieving Green-Sustainability Specifications knowledge base is a huge step in fostering interoperability and knowledge sharing, its content will be limited to the content of the different constituent registers of regulations and standards. Moreover, most regulations/standards normally mostly contain requirement or compliance information.

For example, all buildings are required to be certified at Level 6 of the Code for Sustainable Homes by 2016. With respect to CO_2 emission, a level 6 building is a building with zero carbon emission (CLG, 2006). With respect to internal portable water consumption, a level 6 building will not consume more than 80 litres per person per day (CLG, 2006). However, specifications do not provide the exact sustainable building technologies that can help achieve a level 6 building. Companies and institutions have therefore seized this opportunity and are publishing information about the different building technologies that can help construction professionals meet these specifications. Some of the leading institutions are YouGen (YouGen, 2010), Energy Saving Trust and Green Book Life (GBL, 2010). Their websites have been examined in section 2.3.7.3.

4.5 Critical analysis of the application of semantic web

In this section, a critical analysis of semantic web applications is undertaken. The analysis is classed into two categories. While the first category deals with the technical aspects, the second category deals with the domain application of the semantic web. The first category establishes the extent to which the semantic web technologies have been implemented in practice. This draws from the semantic web technologies reviewed in Chapter 3. For example, the semantic web architecture portrays that real ontologies modelled in OWL can be more useful than lightweight ontologies and when extended to include rules it is even more powerful. The question is how much ontology out there has explored these expressive language and rules capabilities? An attempt to provide an answer to this question will be examined in section 4.5.1. In section 4.5.2, the second category which deals with semantic web applied to different domains will be examined.

4.5.1 Analysis from a technical perspective

In the ontology community ontologies are classified in two categories, lightweight and heavyweight ontology. More meaning can be made from heavyweight ontologies than lightweight ontologies. From the review of the semantic web applications, it emerged that most of the ontologies are lightweight ontologies which is of little benefit with regards to the semantic web vision if not enriched. From an ontological language perspective most ontologies have been developed using XML technologies which do not maximize the full potentials of the semantic web. Furthermore, real life semantic web applications that have explored rules are not available.

While a lot has been done towards the exploration of the development of semantic web applications, most of the applications are yet to be implemented beyond academic laboratories. Most are prototypes at best still to be fully implemented. This is mainly due to the emerging nature of the semantic web technology domain.

4.5.2 Analysis from a domain application perspective

This section analyses the application of the semantic web applications to the different domains including the sustainable building technology domain. From the review in this chapter, it can be pointed out that very limited work has been done with respect to ontology development in the domain of sustainable building technology. This outcome is not by any means a surprise as the semantic web is still at its embryonic stage and most research institutes are preoccupied with developing high level frameworks for specific domains or fragmented ontologies (Lima *et al.* 2003; El-Diraby *et al.* 2005; El-Diraby and Gill 2006). The few research studies with at least some elements of sustainability issues in the built environment are in Macris and Georgakellos (2006), Edum-Fotwe and Price (2009) and Uniclass (Smith *et al.*, 1997). However, it emerged from the literature that there are thousands of basic categorization or very low level lightweight ontologies or taxonomies of information about the domain of sustainable building technologies using basic web technologies. Some notable ones are Sustainable Build (2011), Sustainable Building (2011), gbXML (2010), GBL (2010).

The lack of real ontologies about the domain of sustainable building technology and the publication of thousands of information about them by different government agencies, companies and research institutes underpins the rationale for developing sustainable building technology ontology as part of this research. So far preliminary studies about developing ontologies and exploring their uses in a semantic web environment have already been undertaken as part of the first and second phases of this study (Abanda and Tah 2007; Tah and Abanda 2009; Tah and Abanda 2011). Although most semantic web applications have hardly gone beyond the prototypical stage, they have been implemented in core areas of construction processes such as knowledge management, collaborative design, on-line procurement, on-site information management, communication and collaboration, and change and claim management.

4.6 Conclusion

In Chapter 2, the need of semantic web technologies was identified for the management of sustainable building technologies. It was established that, the main aim of the use of these technologies is in managing sustainable building technology information for their efficient exploitation by end-users thus promoting the uptake of sustainable building technologies into construction projects. Subsequently in Chapter 3, the different semantic web technologies were examined. Although, the different semantic web technologies were established, the challenge still remains in terms of how to specifically use these technologies. What is their level of maturity in different applications?

Thus, a review of semantic web applications to the construction domain has been undertaken. It emerged from this review, that exploratory studies on the applications of the semantic web technologies have been undertaken in managing construction information particularly in the domains of construction education, supply chain, project and construction management, material storage, project design, architecture and graphic designs, etc. However, focusing on the most important concept of the semantic web technology (i.e. ontology development), it was realised that most ontologies in these domains are lightweight ontologies developed using XML and to a better extent RDF. The main limitation of defining ontologies about any domain of discourse using XML and RDF is the fact that it is not possible to maximise the benefits of the semantic web. On focusing the review on sustainable building technologies, it also emerged that most ontologies on this domain are lightweight with some being simple hierarchies on the websites of most companies. From an application point of view, it emerged that although there have been so many research projects, their research output have been nothing more than semantic web prototypes. Although the semantic web is fast becoming a household word in the semantic web research community, most prototypes have been based on OWL ontologies.

With the above analysis, the following key decisions have been established. As there are very limited rich ontologies in the domain of sustainable building technologies, in this study one will be developed. This will include a high level knowledge ontology about the sustainable building technology domain and a more detailed ontology on PV-system in which components design and selection applications will be based. However, due to resource and time constraints available and the fact that there are enormous challenges in exploring an emerging technology such as the semantic web only a prototype will be developed. The next chapter will now focus on the methodology used in this study.

5. RESEARCH DESIGN AND METHODOLOGY

5.1 General

After presenting a theoretical background of the research in Chapters 2 and 3, this chapter seeks to discuss the methodological framework that was used to achieve the aim and objectives of the research as outlined in section 1.4. The chapter will first undertake a review of the most commonly used research paradigms and strategies with the view to establish their respective potential and limitations. The identified limitations of the reviewed research paradigms will guide the selection and formulation of an appropriate methodology and methods used in this study. After justifying the selection of the research strategy, the chapter narrows down to explain how this study was pursued using the selected methodology, thereby demonstrating how the aim and objectives will be achieved. The chapter is divided into four main sections. A review of research methodologies is examined in section 5.2. Based on the review, a methodology for this study is adopted and justified in section 5.3. The framework of the adopted research methodology is examined in section 5.4. The chapter concludes with a summary and challenges in the implementation of the methodology in section 5.5.

5.2 Overview of research methodologies

A voluminous amount of literature categorises philosophical research into quantitative and qualitative perspectives (Moskal *et al.* 2002; Palvia *et al.* 2003; Cresswell 1998). Quantitative research is an inquiry into a social or human problem, largely based on testing hypothesis or theory composed of variables that are measured with numbers and analysed with statistical procedures in order to falsify or prove theoretical propositions (Cresswell, 1998). On the other hand qualitative research aims to understand people and the social and cultural contexts within which they live (Palvia *et al.* 2003; Moskal *et al.* 2002). Consequently, information gathered through qualitative research can be classified into two broad categories: exploratory and attitudinal (Naoum, 2007). Given that each of these research categories has its own strengths and weaknesses, the question of which one to adopt has always been a challenge. While this study will not seek to indulge into a detailed exposition of this debate, it is nonetheless imperative to highlight the key differences that exist between qualitative and quantitative research paradigms

(Bogdan and Biklen, 2003). This is vital in order to be able to choose the appropriate methodology for this study. The differences between quantitative and qualitative research paradigms have been well researched (Bogdan and Biklen, 2003) and are summarised in Table 5.1.

Table 5.1. Differences between qualitative and quantitative research

Qualitative	**Quantitative**
Less generalisable	Easy and more generalisable
Subjective	Objective
Text-based	Number-based
Often no hypotheses or statistical testing	Statistical tests are often used for data analysis
More in-depth information on a few cases	Less in-depth information across a large number of cases
Most process used to formulate theory	Deductive process used to test pre-specified hypotheses or theory
Common methods are focus groups, in-depth interviews, review of documents for types of themes	Surveys, structured interview and observations and reviews of records and documents for numeric data
Depends on the skill and rigor of the researcher	Largely depends on the measurement technique, device or instrument used

Despite the above differences between quantitative and qualitative research, adoption of either strategy would require the identification of literature sources, the establishment of approaches to data collection, the establishment of techniques of data collection, the analysis and presentation of the data collected.

5.2.1 Literature sources

The *identification of literature* sources is an important activity of the literature review of any study. The identified literature sources will be used in the course of the study irrespective of whether the study is quantitative or qualitative. Generally speaking, the two main types of literature sources commonly used in research are the primary and secondary literature sources. A primary source is information in its original format (TCC, 2009), i.e. it must not have been previously published, interpreted or translated. On the other hand, a secondary source is a work that interprets or analyzes an event or phenomenon (Whitson and Phillips, 2009). It is generally at least one step removed from the event and is often based on primary sources. Some common examples of secondary literature sources are textbook, trade journals, magazines and newspapers.

5.2.2 Approaches to data collection

The type of data and information required in any given research depends on the nature of any given study. The researcher is required to establish a systematic way of collecting the required data. In broader terms, two main approaches of data collection approaches exist. These are *the fieldwork research* and *secondary data collection.* The fieldwork research refers to the methods used in the collection of primary data or data from primary sources (Naoum, 2007). Three main examples of fieldwork data collection approaches include the *survey,* the *case-study* and the *problem-solving* approaches.

5.2.2.1 The survey approach

A *survey* is a systematic method of gathering information for (a sample) entities for the purposes of constructing quantitative descriptors of the attributes of the larger population of which entities are members (Groves *et al.*, 2009). Here quantitative descriptors means statistics and statistics are quantitative summaries of elements. The survey is a widely used research method of data acquisition in various domains. Although survey is quite popular in research, over the years, many drawbacks have been associated with this method (Frohlich, 2002). For example, postal mail surveys tend to suffer from low response rates and slow response times (Frohlich, 2002).

5.2.2.2 The case study approach

A *case study* is a story about something unique, special or interesting - stories can be about individuals, organisations, processes, neighbourhoods, institutions and even events (Yin, 2009). The main advantage of a case study is that it provides much more detailed information than what is available through other methods such as surveys. Case studies also allow one to present data collected from multiple methods such as surveys, document review and observation. However, there exist some disadvantages often associated with case studies (Flyvbjerg 2006; Neale *et al.* 2006). Case studies can be very lengthy. Based on the fact that case studies provide detailed information about the case in narrative form, it may be difficult to hold the reader's interest if the case study is too lengthy. Also, there are concerns that case studies are less rigorous than the surveys or other research methods (Neale *et al.*, 2006). The other disadvantage often associated with case study research is that case studies cannot be generalised. That notwithstanding, in the literature case studies have also been prone to over-generalisation, which comes from selecting a few examples and assuming without evidence that they are typical or representative of the population. Despite these disadvantages, case studies are still very popular in research and are highly recommended as useful approaches in software engineering for validating developed software systems (Sommerville, 2007).

5.2.2.3 The problem-solving approach

In the survey and case study approaches, the researcher tends not to interfere with the phenomenon under study. In the problem-solving approach, the researcher reviews the current situation, identifies the problem, gets involved in providing changes that may improve the situation and, possibly, evaluates the effect of his/her changes (Naoum, 2007). This type of research is often called action research (Naoum, 2007).

5.2.3 Techniques of data collection

Secondary data collection is an approach used in collecting data from secondary sources (Neale *et al.*, 2006). It is often called a *desk study approach.* The main difference between primary data collection and secondary data collection approaches is at the level of time and cost. In primary data collection, the data to be collected does not already exist, whereas the secondary involves the summary, collation and/or synthesis of existing studies (Whitson and Phillips 2009; TCC 2009; Naoum 2007).

The *establishment of the data collection* approaches plays an important role in acquiring data from the different data sources. The three main techniques of data collection are *personnel interview (structured, semi-structured* and *un-structured), postal questionnaire* and *sampling (selected* or *random).* The choice of any of these techniques depends on the type of research paradigm being used.

5.2.4 Data analysis

The last stage in a research methodology is the *analysis* and *presentation of data* collected from field work and/or from a desk study. The main activities of data analysis are coding the questions used in the questionnaire surveys, computing the required statistical parameters manually or using appropriate software, interpreting the results and making decisions based on the results. Exploratory data analysis (open-ended questions) is often used in qualitative studies while descriptive methods (measurement of central tendency, normal curve and frequency distribution) and inferential statistical methods (chi-square test, Spearman "rho" ranking correlation) are used in quantitative data analysis (Naoum, 2007).

5.3 Methodology adopted in this study

Based on the different research methodologies reviewed in (Bryman 2001; Bernard 2000; Yin 2009) an exploratory qualitative, case study research was deemed appropriate and adopted in this study. Section 5.3.1 highlights how the adopted methodology fits the context of this study while section 5.3.2 establishes why the adopted methodology was implemented in this study.

5.3.1 Exploratory research methodology

Any domain of discourse can best be understood by using exploratory research. Exploratory research is considered appropriate for application in relatively new and evolving fields such as the information systems domain. Currently, the semantic web is one of the most nascent technologies considered within a wider information system domain. Within the context of this study, the rationale for an exploratory research is even stronger as the semantic web being a new and evolving field is being investigated to be applied in modelling information about another emerging field, the sustainable building technology domain. Exploratory research provides an insight into and/or a comprehension of an issue or situation. Exploratory research is mostly utilized in qualitative studies. This is because the exploratory use of open-ended questions and probing aimed at providing participants in a survey the opportunity to respond in their own words is grounded concept in qualitative research. The outcome of an exploratory research is the establishment of primary findings and claims which will dictate the path of subsequent procedures or activities of the study. Based on the findings or claims, evidence should be formulated to support the findings or claims. In research, evidence is taken to mean a convincing argument in support of a claim or hypothesis, a justification from data analysis, and a *proof-by-demonstration.* In the domain of artificial intelligence, prototypes can provide a piece of evidence in support of a claim (Pan, 2006). Like in social sciences - where case studies have been used in evaluation research (Yin 2009, Patton 2002; Neale *et al.* 2006), generally, in information systems, case study research is appropriate in validation of prototypes developed in the context of an exploratory study. In Yin (2009) it is suggested that case studies can be very valuable in generating an understanding of reality, and describes the single, in-depth case study as a "revelatory" case. In Zelkowitz and Wallace (1998), it is reported that in software engineering, case studies facilitate the testing of theories and the collection of data in an "unmodified setting". Thus, testing systems with real data instead of simulated data, using a real-world case study to validate a software prototype is often recommended (Sommerville, 2007). Some examples of the application of case studies in validating prototypes have been reported in Clutterbuck *et al.* (2009), Poh (2005) and Thompson (1997).

5.3.2 Justification of methodology

In order to justify the exploratory qualitative case study research adopted in this study, it is necessary to re-visit the aim of this study. As stated in Chapter 1, the study aims to investigate the use of an emerging semantic web technology on an emerging sustainable building technology domain. An exploratory research is suitable for an emerging technology such as the semantic web. By exploring the semantic web, new knowledge and emerging technologies are uncovered. An example of new semantic web technology is the SWRL which can be used in modelling rules in a semantic web environment. The uncovered knowledge is harnessed in developing applications that portray the semantic web capabilities. An example of a semantic web application is a decision-support system for the selection of PV-systems. To prove the semantic web capabilities, a case study is employed to support the prototype. According to Yin (2009), a case study design should be considered when: (a) the focus of the study is to answer the "how" and "why" questions; (b) you cannot manipulate the behaviour of those involved in the study; (c) you want to cover contextual conditions because you believe they are relevant to the phenomenon under investigation; or (d) the boundaries are not clear between the phenomenon and context. In the context of this study, the following investigative questions justify the application of a case study: Why semantic web technologies? How can the semantic web be best queried? How can knowledge about sustainable building technology be easily accessed?" How successfully can the sustainable building technology knowledge be managed in a semantic web environment? In an attempt to answer these questions, modelling sustainable building technology knowledge using appropriate semantic web technologies is key to this research. This can be achieved through a proper understanding of both domains and how both can be related. Figure 5.1 highlights the OWL relationship between the two domains. In relating the two models, a more general class of any ontology *thing* (Noy and McGuinness, 2001) which represents tangible and intangible components of the universe has been used. The two domains subsume the class *thing*.

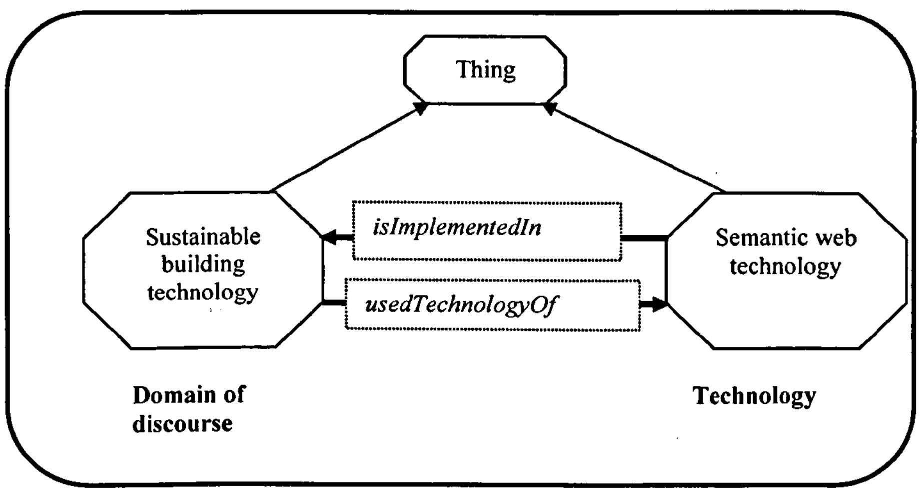

Figure 5.1. OWL relationship between sustainable building technology and semantic web technology domains

To understand how best to use the semantic web ("*usedTechnologyOf*") there is need to first understand the problem domain (in this case the sustainable building technology domain). This is achieved through a thorough review of literature and informal consultations with experts at conferences and exhibitions. The conferences and exhibitions provided a suitable platform for the exchange of knowledge. Furthermore, the displays by manufacturers at exhibitions provided an understanding of the working principles and mode of operations of the different sustainable building technologies.

Secondly, an exploratory study of the semantic web domain is undertaken in order to identify the components of semantic web that can be applied in modelling knowledge about the sustainable building technology domain. To understand how best to implement semantic web (*"isImplementedIn"*) in modelling knowledge about sustainable building technology, the key components suitable for applicability in the domain of sustainable building technology are established.

From the above analysis the use of an exploratory research method, prototyping and case study research have emerged. In the ensuing sections a methodology framework will be examined and will bring out the relationship between them.

5.4 Methodological framework

From the literature review in Chapter 3, it was realised that the development of an ontology knowledge-based system cuts across three main areas of artificial intelligence and semantic web research. These major areas are the software, knowledge and ontology engineering. The bases of these relationships are twofold. Firstly, the process of developing an ontology knowledge-based application entails developing an ontology as a sub-task. This relates ontology engineering to knowledge engineering. Secondly, to facilitate the process of ontology development, the use of suitable software is often recommended. This often leads to writing computer programmes to access, manipulate or even extract data from a semantic web repository. This is the relationship between ontology and software engineering. The research framework presented in Figure 5.2 takes into consideration the links between the three fields. However, the core of the framework is based on CommonKADS - a knowledge engineering methodology upon which the other core aspects such as ontology development, an aspect of ontology engineering is grounded. Also, the framework will reveal where the case study fits with respect to the different stages of the CommonKADS methodology.

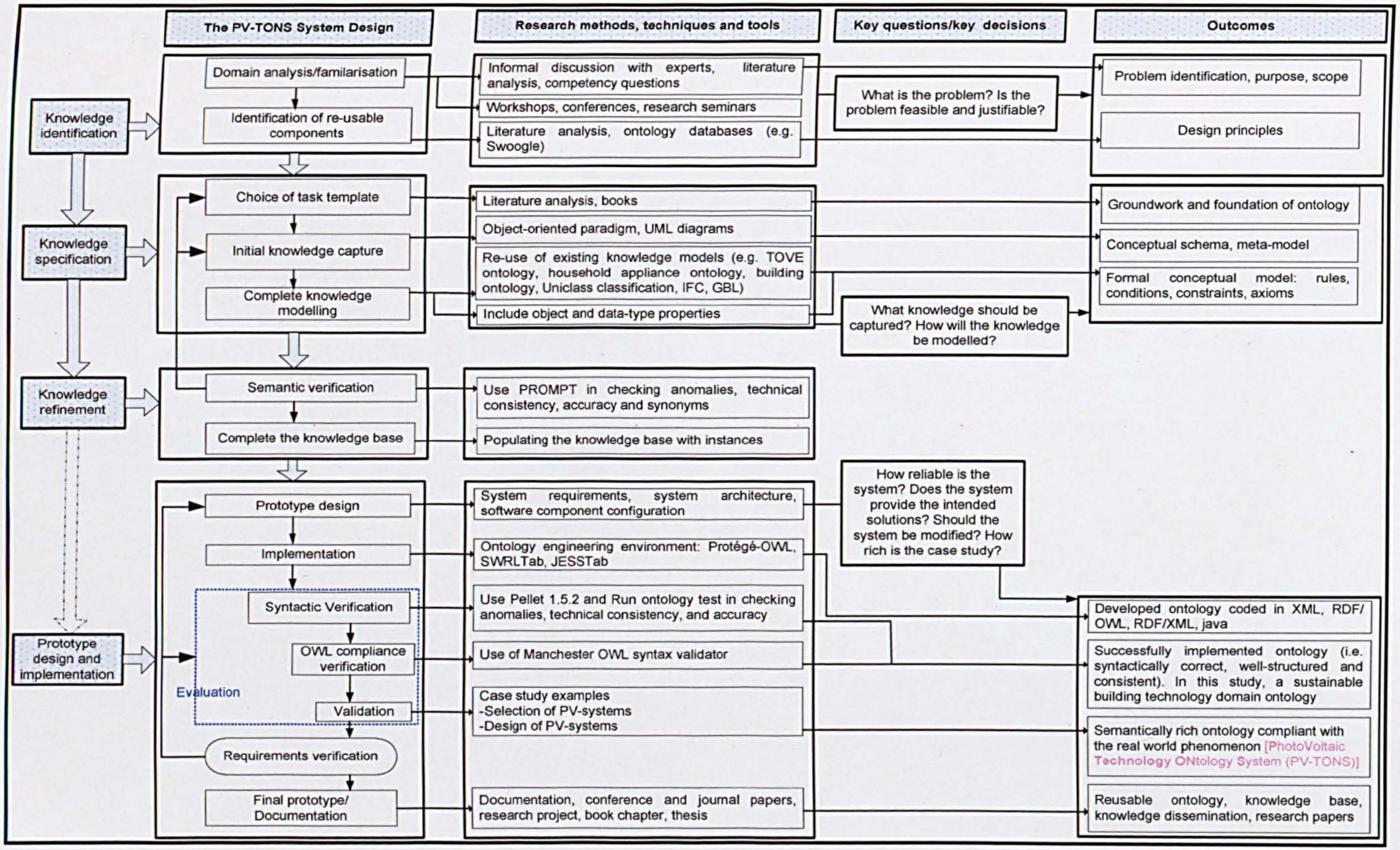

Figure 5.2. Methodological Framework

The four main stages that are crucial in the methodology are knowledge identification, knowledge specification, knowledge refinement and the development of a prototype system as shown in Figure 5.2. These will be discussed in the ensuing sections.

5.4.1 Knowledge identification

The two main goals of the knowledge identification stage are to survey the knowledge items and prepare them for specification. To achieve these goals two main activities have been undertaken in this study. These are familiarisation with the domains of sustainable building and semantic web technologies (see Chapters 2 and 3) and the identification of re-usable knowledge components.

5.4.1.1 Domain familiarisation/analysis

The first activity in knowledge identification is *domain familiarisation/analysis* which can be broken down into domain familiarisation and domain analysis. *Domain familiarisation* is the starting point of this study. An intensive literature study was undertaken. Given that this study deals with two emerging domains, i.e. sustainable building and semantic web technologies, the literature study was undertaken firstly on the former then secondly on the latter. Based on the reviewed literature of sustainable building technologies, a thorough *domain analysis* was undertaken. This entails making key decisions as to which area of sustainable building technology to focus on? What is the characteristic nature of information about sustainable building technology? Who are the renowned authors in the field of sustainable building technology? etc? Different knowledge sources and experts contributed significantly to the achievement of the domain familiarisation/analysis. Contrary to the traditional lack or limitation of knowledge sources with most emerging technologies, the domain of sustainable building technology is well-researched, having many peer-reviewed publications. The main literature sources identified are peer-reviewed papers, text books and electronic documents. While peer-reviewed papers, textbooks and electronic material were greatly exploited by the researcher, the researcher also authored some peer-reviewed papers. Writing of these peer-reviewed materials served as quality audit checks and hence enhanced the general quality of the research. Amongst these peer-reviewed papers are a research project by the International Labour Office, one book chapter, ten conference papers and five articles submitted for journal consideration (the full list of these publications can be found in appendix 9.1). Out of the five articles four have been accepted and published while the outcome of one is still pending. The feed-back from the reviewers for conferences and comments from the audience during conferences were taken into consideration in shaping this study. Above all the comments from journal reviewers were a vital knowledge source. Other important knowledge sources include websites of some government and non-governmental agencies publishing documents about the domain of sustainable building technologies. The three government agencies renowned in the field of sustainable building technologies were key knowledge sources for this research are the Building Research Establishment, Energy Saving Trust and the Carbon Trust. Continuing Professional Development (CPD) training events on sustainable building technologies were another major knowledge source about sustainable building technology. During the CPD training sessions, informal consultations were held with sustainable building technology experts who contributed to shaping the knowledge models in this study. Consequently, the elicitation of knowledge on the domain of sustainable building was purely a desk study and by consultations with domain experts during CPD training sessions.

Like sustainable building technology, knowledge about semantic web technology was obtained through exploring the literature about this new technology. Given the fact that the semantic web is emerging, some major semantic web technology websites such as those of the Protégé-OWL (Protégé, 2010), Jena (Jena, 2010), Pellet (Clark and Parsia, 2011) and Jess (Strauss, 2007) were explored. Furthermore, *knowledge experts* were also used in providing guidance where necessary. Unlike the sustainable building technology domain where real technologies exist and can be characterised (e.g. PV-system technology), thousands of researchers are developing different semantic web tools with most of these tools at the moment being unstable. As a result, the identification of key stakeholders (i.e. identification of knowledge partners) in the domain of semantic web technology was imperative. Currently, Stanford University, Southampton University, Manchester University and Karlsruhe University are playing leading roles in the advancement of the semantic web technology. The researcher undertook basic programming training in some key areas of the semantic web at the University of Manchester and in the School of Technology at Oxford Brookes University. The specific outcomes of this knowledge identification stage are an insight into the domain of sustainable building and semantic web technologies, the identification of methodologies, tools, languages and programming environments to be used in this study.

5.4.1.2 Identification of re-usable knowledge components

The next activity of the knowledge identification phase is the identification of potential *re-usable knowledge components.* In the spirit of ontology engineering, existing ontologies were reviewed for possible re-use. This requires a knowledge engineer to use an existing knowledge model of a domain and eliminates the task of validation of knowledge or ontology models by domain experts. However, based on the review of the literature there were no appropriate knowledge models that could be used. A document analysis was conducted and knowledge was abstracted from peer-reviewed sources and renowned websites about the domain of sustainable building technology. Some examples are building construction techniques classified by (BRE, 2010), Sustainable energy technology classified by BRE, Energy Saving Trust, Carbon Trust (BRE, 2010), Building construction elements and products classified by Uniclass (Smith *et al.*, 1997). One major outcome of exploring sustainable building technology literature sources is the fact that its domain characteristics (i.e. information publication formats, use of vocabulary of term, size of the information, etc.) guided the path to which the review of semantic web technology was pursued. For example, ontology development is the main line of focus as against ontology merging and/or ontology mapping. In other words, while a detailed analysis on ontology development will be conducted, other aspects of ontology engineering such as ontology merging and/or mapping may simply be used whenever there is need.

5.4.2 Knowledge specification

The main aim of knowledge specification is to establish the concepts and relationship about a domain of discourse. This task is usually achieved through three main activities. These are *choosing the task template, initial knowledge capture,* and *complete knowledge modelling*

5.4.2.1 Choosing of task template

The first activity involves choosing an appropriate *task template*, a partial knowledge model in which inference and task knowledge are specified. Based on the different types of task templates reviewed in Schreiber *et al.* (2000), the classification task template was chosen.

5.4.2.2 Initial knowledge capture

The *initial knowledge capture* requires a knowledge engineer to use knowledge elicitation techniques to capture knowledge from a domain expert, from literature sources or re-use of existing knowledge models. The knowledge elicitation techniques to be used depend significantly on the knowledge source. In this study and as earlier mentioned in section 5.4.1, online content, textbooks and peer-reviewed papers proved to be a useful source of information especially in relation to attributes of sustainable building technologies. Given that the focus here was to establish a structured knowledge model, and that the knowledge sources provided semi-structured or hierarchical knowledge model about sustainable building technologies, the qualitative content analysis approach was used. The qualitative content analysis approach is defined as an approach for the analysis of texts and documents in which researchers seek to qualify content in terms of pre-defined categories in a systematic and replicable manner (Bryman and Bell 2007; Hsieh and Shannon 2005; Elo and Kyngäs 2008). One of the most popular ontology methodologies that uses qualitative content analysis technique is the PROMPT methodology of aligning/merging ontologies or conceptual knowledge developed by Noy and Musen (2003). The advantage of using the PROMPT technique is that it semantically validates the knowledge model.

5.4.2.3 Complete knowledge modelling

The completion of the knowledge model entails including the relationship between classes as identified in the initial knowledge capture stage. In ontology language paradigm these relationships are called object properties. The inverses of the object properties can also be stated. The attributes of classes otherwise known as data-type properties are also stated. The annotation properties are also established at this stage.

However, it is best implemented in a software environment where each annotation property is directly tagged to the concept in the knowledge model.

5.4.3 Knowledge refinement

During the knowledge refinement phase two main activities are carried out:

- The semantic verification of the knowledge model;
- And the completion of the knowledge base by adding domain knowledge instances.

Although by using the PROMPT technique in semantically verifying concepts in the sustainable building technology domain as highlighted in section 5.4.2.4, errors were still detected. Thus, in this stage, the PROMPT technique is implemented again to minimise the risk of semantic errors. The last activity in this phase entails the completion of the knowledge base with concept instances. This will be best done in a software environment. This is examined in the ensuing section.

5.4.4 Prototype development

As some errors are unavoidable during implementation, there is bound to be iterative evaluation to ensure the syntactic and semantic correctness of the knowledge model. Thus, the prototype development methodology will be applied in this phase. As discussed in section 1.5.1, the prototype to be designed will take into consideration end-users with minimal computer science skills. Some examples of end-users include sustainability building technology consultants, developers and home builders. The phase is made up of *prototype design, prototype implementation, prototype evaluation, verification of system requirements fulfilment* and *documentation* of the final prototype.

The *prototype design phase* comprises of two main activities. These are the establishment of the system requirements and the system architecture. The second activity of prototype development is the *prototype implementation* activity. This activity is about how the knowledge model will be input into the different components of the system architecture. The transfers of OWL ontology from Protégé-OWL to a storage environment (e.g. MySQL or as an OWL file) or into a reasoning environment (e.g. Jess) are examples of prototype implementations. The conversion activity from UML to OWL can be achieved through manual or automatic processes using UML converters to OWL. The former process is slow but yields the anticipated results. The latter is fast but yields results with loss of data. To gain in speed and quality of data both methods were used in this study. The ArgoUML software was used to automatically convert UML to OWL (ArgoUML, 2010) and the converted knowledge structure was then manually enriched using the "Ontology Development 101" methodology (Noy and McGuinness, 2001). ArgoUML is a leading UML programming tool that can be used to automatically convert UML to OWL in Protégé-OWL.

It is important also to note that the OWL model representing the sustainable building technology domain and the PV-system are both domain ontologies. Although these ontologies can further be re-used in other applications, they are lacking in terms of high level reasoning that exploits the full potential of the semantic web technology. Based on the purposes of this study, the PV-system ontology is extended to include SWRL rules that deal with the case study applications. Rules elicitation was conducted through the exploitation of UML properties and the laddering knowledge acquisition techniques reviewed in Schreiber *et al.*(2000). It is important to note that the complete knowledge model in Protégé-OWL is an empty knowledge structure "filled with holes" or "place holders". It includes definitions or place holders for ontology components such as classes, properties and instances. Therefore, the *completion of the ontology knowledge base* with instances is an important activity of this phase.

However, the population of the knowledge base generates anomalies that require to be checked. Therefore, an *evaluation* (i.e. syntactic verification) of the prototype is an important activity of prototype development. A very common example of anomaly that requires syntactic evaluation is the non-compatibility of data-type property with its value. For instance, if a data-type property is defined as a string and an integer value is attributed, a likely error message will emerge. Syntactic verification is an important activity that ensures implementation errors are eliminated or minimised. Protégé-OWL plug-ins such as Run ontology test and Pellet reasoner were used in checking that the ontology knowledge base is syntactically correct. Run ontology test is a plug-in in

Protégé-OWL used to check if an OWL ontology language (Lite, DL and Full) is being correctly used. Pellet is an OWL 2 reasoner which provides standard and cutting-edge reasoning services for OWL ontologies and check anomalies in an ontology knowledge base. Common anomalies include violation of subsumption concept, instance checking, and ontology inconsistency. After the syntactic verification for anomalies, the ontology knowledge model is checked for ontology language compliance. In this case it was checked for OWL compliance using the Manchester OWL syntax validator. Checking of anomalies led to the refinement of the knowledge model. This is a continuous cyclic process until the final desired product is obtained.

After syntactic verification, a case study was employed to validate the prototype. The case study is designed in such a way that they can fulfil the prototype requirements or what the prototype is intended to do. This is known as the *validation of prototype requirements*. It is important to note that the prototype requirements verification is an iterative process, where it is continuously conducted until the final desired prototype is achieved.

After the prototype validation, the prototype can now be documented. The documentation of the prototype could be in the form of conference and/or journal publications, textbooks or even over the web. Ontology documentation is very important as poor documentation of onologies is a major barrier towards ontology maintenance, use and re-use and knowledge sharing. This *documentation activity* is the last activity of the prototype development. The documentation can be in peer-reviewed conference or journals, text books, research project reports or thesis. In this study, the initial prototype development methodologies were presented at conferences and feedbacks were used to improve the papers. Furthermore, part of the prototype was accepted for publication in the journal of Advanced Engineering Informatics while the complete prototype has been submitted to the journal of Information Sciences.

5.5 Conclusion

This chapter has established the research methodology to be pursued in this thesis. To gain an insight into the opportunities embodied in the semantic web, the research undertakes an exploratory approach. This approach led to some major findings such as the different technologies about the semantic web. A key point was how these technologies are different from the current web technologies. To gain an insight on how these technologies can be used in managing sustainable building technology knowledge, knowledge and ontology engineering methodologies have been investigated. These methodologies were applied in the development of a prototype system. This prototype system will serve to demonstrate the extent to which semantic web technology can be applied in managing sustainable building technology knowledge. The examined methodology leads to the: development of a sustainable building technology domain ontology, the development of the PV-system selection and design decision-support system. Based on the sheer size of the information about the sustainable building technology domain, the application of the methodology examined in this chapter was divided into two. In Chapter 6, the first application is about the acquisition of sustainable building technology knowledge. Second, the sustainable building technology knowledge captured in Chapter 6 is implemented in Chapter 7.

6. KNOWLEDGE ACQUISITION IN THE SUSTAINABLE BUILDING TECHNOLOGY DOMAIN

6.1 General

In order to develop a decision-support system about any domain, it is essential to capture the complex structure and dynamics of the domain. In the case of this study, it was necessary to understand the complex knowledge structure of the sustainable building technology domain. Thus, the main objective of this chapter is to develop sustainable building technology conceptual knowledge models that will be implemented in a software environment in Chapter 7. Although the conceptual modelling process has been largely based on the CommonKADS methodology discussed in Chapter 5, the process was still rather exploratory than just being a straightforward conversion of a manual process into a computer-based process which is usually the case with knowledge engineering processes where the domain is well understood and the knowledge readily available.

This chapter uses the CommonKADS methodology previously examined in Chapter 5 in developing sustainable building technology and PV-system knowledge models. In the application of CommonKADS, the conceptual modelling principles reviewed in Chapter 3 were used. The abstraction and verification of knowledge models, a major step of the knowledge engineering methodology was facilitated by the PROMPT alignment/merging technique. The application of the PROMPT ontology alignment/merging technique on modern methods of construction has been explicitly demonstrated. For reasons of time constraints, only the results of the application of the PROMPT alignment/merging technique in the generation of other knowledge models such as for the renewable energy technologies has been presented. The chapter also seeks to discuss the development of the conceptual knowledge framework of this study. The framework will be implemented in software environments in the Chapter 7.

6.2 Background

A clear understanding of the domain knowledge is the most important aspect in the design of a knowledge-based system. Accordingly, the aim of this chapter is to provide an understanding of the sustainable building technology domain. The understanding of the domain includes understanding the key concepts, features and individuals in the sustainable building technology domain. This implies that a sustainable building technology knowledge model should be able to provide answers to basic queries such as: What are the different kinds of sustainable building technologies? Who are the main suppliers of sustainable building technologies in the UK? How sustainable are the sustainable building technologies? Answers to these and similar questions can only be answered if domain knowledge about the sustainable building technology is established. This can be achieved by undertaking knowledge acquisition, a common knowledge engineering activity that involves the elicitation, collection, analysis, modelling and validation of knowledge for knowledge engineering and knowledge management projects (Milton, 2003).

In Chapter 2, an overview of the sustainable building technology domain was undertaken. The positive outcome of that overview was an insightful appraisal or understanding of the sustainable building technology domain. The advantages, characteristics and barriers to the uptake of sustainable building technologies are some of the key features that emerged from the appraisal. Knowledge dissemination was particularly identified as a key in overcoming some of the barriers in the uptake of sustainable building technologies. In this regards, an investigation of the semantic web technology was reviewed in Chapter 3. One of the major outcomes of the review of semantic web was the use of object-oriented modelling techniques as the first step in capturing domain knowledge. Based on this and other outcomes which are mostly the advantages of the semantic web technology, a methodology was established in Chapter 5. The purpose of the methodology is to show how the aim and objectives of this study will be achieved. Key to the task of achieving the aim and objectives of this study is the development of a semantic web prototype system. As depicted in the methodological framework, the key stages to the successful development of a prototype are knowledge identification, knowledge specification and knowledge refinement. It is based on the knowledge models developed in these stages, that the prototype system is developed.

In a research endeavour of this nature with limited resources, it is not possible to tackle all the available sustainable building technology products. In this chapter, a two stage approach will be undertaken. In the first step, a generic knowledge model about a representative cross-section of sustainable building technologies will be developed to illustrate an overview of sustainable building technology. The second step presents a detailed sub-concept of sustainable building technologies and PV-systems. The focus will be on PV-systems for reasons outlined in Chapter 1 (e.g. enormous extent of sustainable building technology domain). This will hopefully help in developing insights that can be applicable to the full range of sustainable building technologies. In the ensuing sections, a knowledge engineering approach based on the CommonKADS methodology will be used to acquire knowledge about the sustainable building technology domain. The three major steps used in the CommonKADS methodology are the knowledge identification, knowledge specification and knowledge refinement.

6.3 Knowledge identification in sustainable building technology

The two main activities undertaken in this stage are domain familiarisation and identification of potential re-usable knowledge models. During the domain familiarisation activity four main information sources were reviewed. The first source includes reviewing written information in manuscripts (i.e. books, peer-reviewed papers, official government documents, etc.). The second source was the review of relevant websites about sustainable building technologies. Some examples are the websites of Energy Saving Trust, Carbon Trust, Renewable Energy Association, Building Research Establishment and YouGen, etc. as previously discussed in Chapter 2. The third source of information was through informal discussions with experts in conferences about sustainable building technology domain. The fourth information source was from institutions offering training on micro-generation technologies. Some of the major sessions attended by the researcher were on: sustainable building technologies offered by the Centre for Construction Innovation, Manchester, UK and the Construction Industry Environment Forum, also in Manchester, and renewable energy management and finance in European Energy Centre and Centro Studi Galileo, Edinburgh Napier University, Scotland. In the case of identifying potential re-usable knowledge components, an extensive literature and database search about different knowledge models was undertaken. This activity led to the identification of existing models (Gamma *et al.* 1997; Shalloway and Trott 2004; Schreiber *et al.* 2000) and based on the type of inference to be executed about the domain of sustainable building technologies (e.g. What are the different kinds of sustainable building technologies?) , the *task template* was adopted and is discussed in the ensuing section.

6.4 Knowledge specification of sustainable building technology

The three main activities in the specification stage are choosing the type of task template, partial construction of initial domain schema and complete construction of the domain schema.

6.4.1 Choosing a type of task template

A task template is a partial knowledge model in which inference and task knowledge are specified (Schreiber *et al.*, 2000). Task templates can be used by the knowledge engineer as a template for a new application and thus support top-down knowledge analysis (Schreiber *et al.*, 2000). Based on the review of the different task templates in Schreiber *et al.* (2000), the *classification task template* was deemed appropriate for use in the sustainable building technology application and hence was adopted. The reasons for this choice are two-fold. Firstly, the classification task template already contains a domain schema. For instance, the schema specifies the key components of a class such as attributes and methods which can be used in inferencing. Secondly, the inference structure of the classification task template appears to fit well with the sustainable building technology application to be developed. Answers to queries like listing the different types of sustainable building technologies can easily be deduced using any inference engine designed based on object-oriented principles.

6.4.2 Partial construction of the initial domain schema for sustainable building technology

Taking into consideration the problem statement, three main criteria were set in determining concepts to be included in the sustainable building technology domain. These are concepts of technologies that address the performance of buildings with respect to the three principles of sustainable development, abstraction of concepts and identification of existing developed concepts that can be re-used, and identification of the interaction of other knowledge models with sustainable building technology domain model. These criteria are examined in sections 6.4.2.1, 6.4.2.2 and 6.4.2.3.

6.4.2.1 Sustainability performance criteria for modelling of partial concepts

From the point of addressing building performance, technologies that aim to foster sustainability have been considered. Many governments have developed green credentials or set standards for assessing building systems performance. This entails assessing the technologies used in the building envelope against some minimum requirements often called green credentials. In the US, the Leadership in Energy and Environmental Design (LEED) is the most commonly used and widely known building assessment system (Retzlaff, 2008) while the BRE Environmental Assessment Method (BREEAM) is popular in the UK (Alnaser *et al.*, 2008). BREEAM sets standards for best practice in sustainable building design and addresses the performance of buildings in the areas of *energy* and *CO_2 emissions, water , materials, surface water run-off, waste, pollution, health & well-being, management, ecology* (Alnaser *et al.* 2008; CLG 2010). Concepts related to technologies developed to mitigate environmental impact in relationship with the afore-mentioned areas have been considered in the establishment of top level concepts of the sustainable building technology domain. For instance, *greywater recycling* and *rainwater harvesting* are water technologies that can improve the water performance of buildings. In no particular order, the concepts considered are *building construction technology, water conservation technology, greywater recycling, rainwater harvesting, smart system technology, waste minimisation technology, renewable energy technology, geothermal, biomass, tidal, wind, solar, solar thermal, PV-system technology, hydro, building construction system, traditional method of construction, modern methods of construction, non-off-site manufacture, tunnel form, off-site manufacture, modular, hybrid, volumetric, panellised, open panellised system, composite panellised system, solid panellised system, closed panellised system, building construction material* and *building construction element.*

A major challenge in this list of concepts about the different components of the domain of sustainable building technology aimed at facilitating building performance is how to logically assemble them into a knowledge model in order to facilitate reasoning for decision-making. In knowledge engineering two methods are often used in assembling concepts in a domain in generating knowledge models. The first is by building the knowledge models from scratch and then soliciting domain experts to validate the complete knowledge model. The second method is by re-using existing knowledge models. The second has an advantage over the first in the sense that in the second method domain experts' opinion is not required in validating the knowledge model which is often time consuming and too expensive. Light validation techniques are often used, or an appropriate knowledge acquisition technique which auto-validates the knowledge model can be used. In this study, disparate knowledge models were identified and an acquisition technique based on PROMPT (Noy and Musen, 2003) was used. This technique ensured the knowledge model captured were semantically right. The details of this technique and how it was applied will be examined in the ensuing section.

6.4.2.2 Partial knowledge modelling using existing knowledge models

A major activity of the knowledge identification phase is the re-use of existing domain knowledge models. In fact, the re-use of knowledge is highly recommended in ontology development. There are two approaches of re-using knowledge models. The first is by using automatic tools if your knowledge models exist in a well-structured, identical format, particularly with respect to ontology knowledge models. A common automatic tool for aligning/merging ontology knowledge models is the PROMPT interactive suite developed by Noy and Musen (2003). The second method of re-using existing domain knowledge models is by manually comparing the different ontologies through aligning/merging the different components of the knowledge models. This is often used in cases where the individual knowledge models exist in different format. This was adopted as most of the components to be aligned or merged existed in manuscripts, electronic forms available on websites of research and government institution. Furthermore, because the existing knowledge models required further enrichment because they existed in simple hierarchical forms, manual integration was the better alternative. Based on the literature review, seven main concepts were identified and abstracted. The components were identified based on their role in improving building performance with respect to the principles of sustainable development. These are *modern methods of construction, renewable energy technology, smart system technology, water conservation technology, waste minimisation technology, building* *construction material,* and *building construction element.* It is important to note that, of these seven concepts the first five were abstracted from different documents while the last two were lightweight ontologies from the Uniclass classification were re-used. The re-used lightweight ontologies were not rich enough, thus some attributes were included to meet the requirements of sustainable building technology. Based on the different knowledge levels in the above knowledge concepts to be used, modern methods of construction exhibit more characteristics that are suited to ontology merging and alignment concepts. Hence, the PROMPT methodology will be used in demonstrating the merging and alignment process of the abstracted concepts of modern methods of construction. With regards to the others, the results based on the application of this methodology will be presented.

Modern methods of construction: This concept embodies methods of construction that use emerging innovative systems manufactured both in the factory and on-site. This can further be broken down into *off-site* and *non-off-site manufacture.* Like most sustainable development terminologies, there is no universal agreed definition of modern methods of construction. However, many and sometimes conflicting definitions can still be found (e.g. Burwood and Jess 2005; OPDM 2005; EST 2005; Barker 33 2006; POSTnote 2003). The definition adopted for this study is that of Barker 33 (2006) which is more elaborate than, and encompasses most of the other definitions. It states that "Modern methods of construction are about better products and processes. Modern methods of construction are therefore, more broadly based than a particular focus on product. They engage people to seek improvement through better processes in the delivery and performance of construction". Perhaps the non-universality of its definition has led to the differences in the various categorisations of modern methods of construction. Four main modern methods of construction categorisations were reviewed (CLG 2008; Hall 2006; Ross 2005; NHBC 2006). These were manually aligned and merged using the PROMPT methodology (Noy and Musen, 2003) reviewed in Chapter 3. A major advantage of using the alignment/merging technique is that it semantically verifies the knowledge model being developed. The alignment and merging process of the different classifications is outlined through the use of sketched diagrams in Figures 6.1, 6.2 & 6.3.

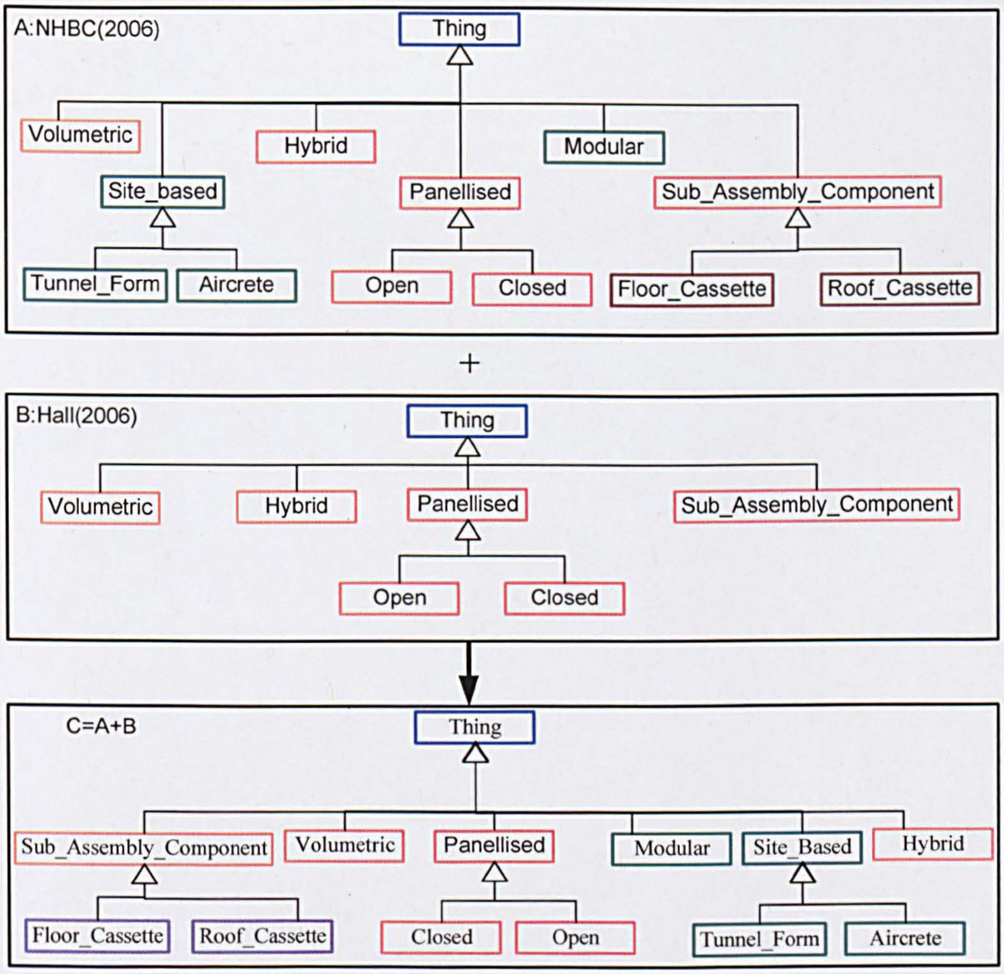

Figure 6.1. Merging concepts of modern methods of construction[5]

Based on the application of the procedures of the merging process of Noy and Musen (2003) on the abstracted concepts A (NHBC, 2006) and B (Hall, 2006), C (A+B) was obtained as the merged ontology. The key steps in obtaining C are as follows:

- Concepts common to both A and B have been retained in C. These concepts are denoted in red and include panellised, closed, open, hybrid, volumetric, and sub_assembly_component systems;

- Concepts not common to both denoted green were simply copied onto C. These are modular, site-based, tunnel form and aircrete systems;

[5] Abstracted from NHBC(2006) and Hall (2006)

- Inherited concepts are denoted in pink. These include the subclasses of sub_assembly_component which are floor cassette and roof cassette;

- The overall superclass denoted in blue that supersedes any ontology was simply adopted. This is the *thing* concept denoted in blue.

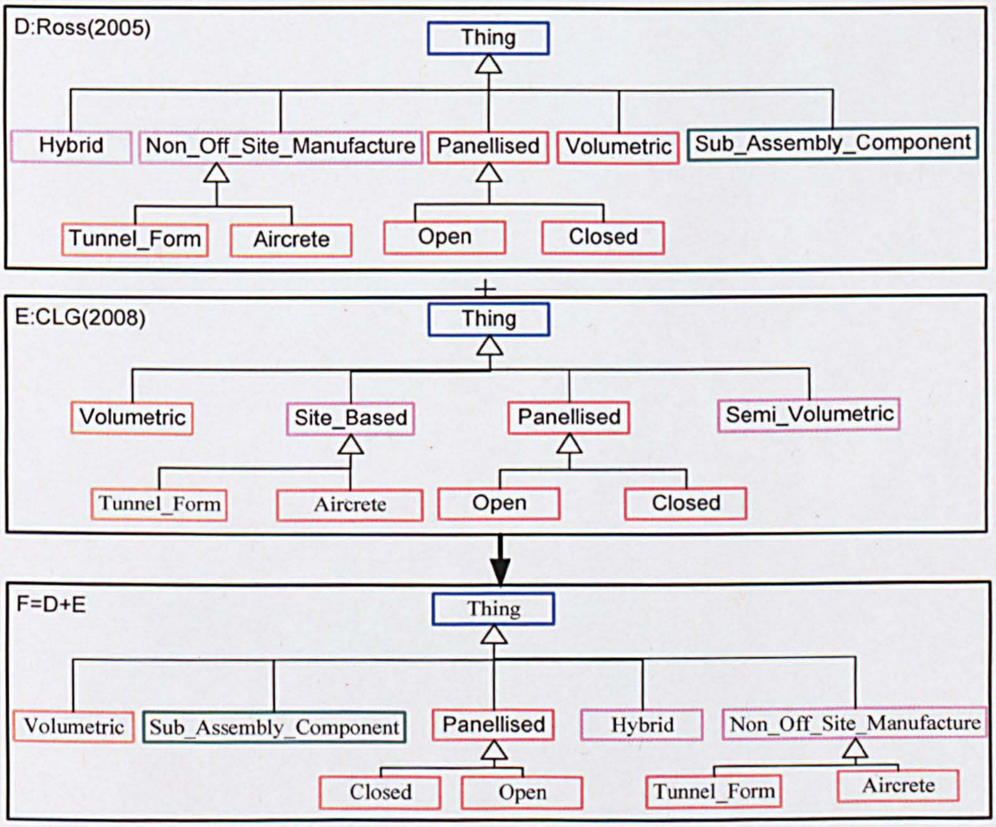

Figure 6.2. Merging concepts of modern methods of construction[6]

Based on the application of the procedures of the merging process of Noy and Musen (2003) on the abstracted concepts D (Ross, 2005) and E (Hall, 2006), F (D+E) was obtained as the merged ontology. The key steps in obtaining F are as follows:

- Concepts common to both D and E have been retained in F. These concepts are denoted in red and include panellised, closed, open, volumetric, tunnel form and aircrete systems;

[6] Abstracted from Ross (2005) and Hall (2006)

- Concepts not common to both denoted in green were simply copied onto F. This includes sub_assembly_component systems;

- Existence of synonyms denoted in purple: Non-off-site manufacture is used in Ross (2005) and site-based construction is used in CLG (2008). Also hybrid is used in Ross (2005) while semi-volumetric system is used in CLG (2008). According to Noy and Musen (2003), the ontology engineer has the discretion to adopt any of the concepts in the merged ontology. In this case, non-off_site manufacture and hybrid systems were adopted in the merged ontology F;

- The overall superclass denoted in blue that supersedes any ontology was simply adopted. This is the *thing* concept denoted in blue.

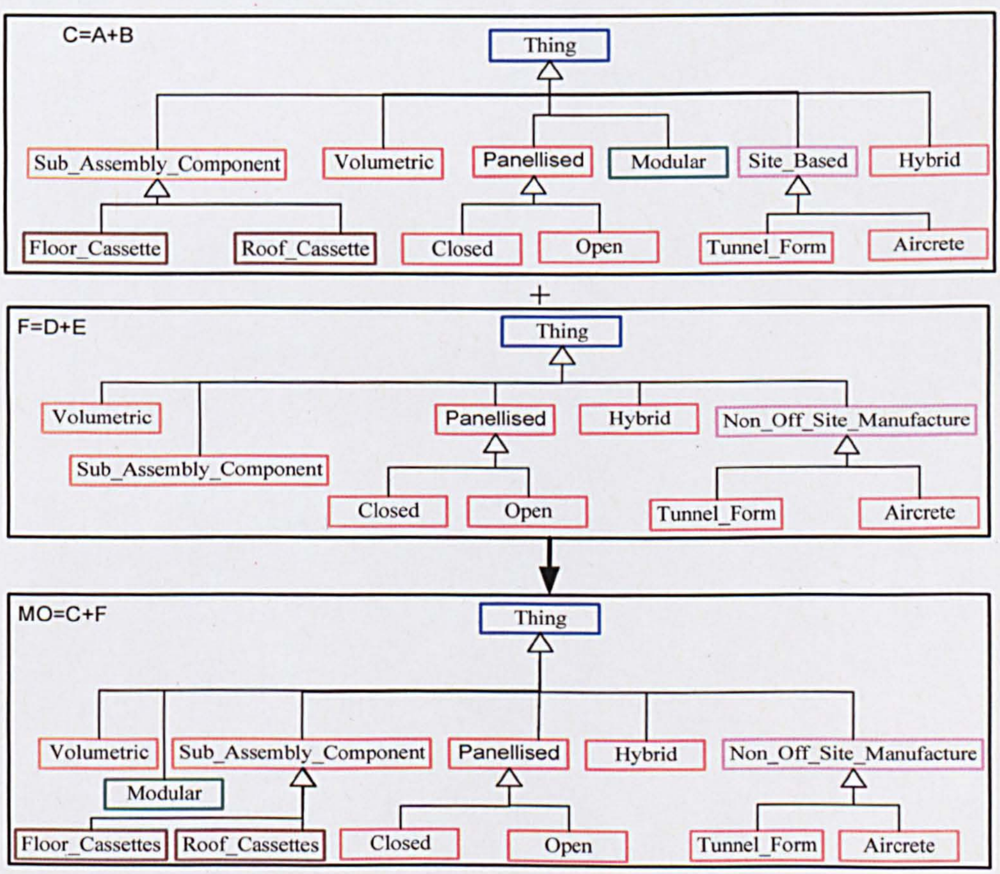

Figure 6.3. Merged concepts in modern methods of construction[7]

[7] Merged from Figures 6.1 & 6.2

Based on the application of the procedures of the merging process of Noy and Musen (2003) on the ontologies D (Ross, 2005) and E (Hall, 2006), F (D+E) was obtained as the merged ontology. The key steps in obtaining the F are as follows:

- Concepts common to both C and F have been retained in MO. These concepts are denoted in red and include panellised, closed, open, volumetric, tunnel form, aircrete systems, hybrid and Sub_Assembly_Components;

- Concepts not common to both denoted in green were simply copied onto MO. This includes modular systems;

- Existence of synonymous terms denoted in purple: Site based construction is used in the C ontology and non-off-site manufacture is used in F ontology. Like in the previous case, non-off_site manufacture systems were adopted in the merged ontology MO;

- Inherited concepts are denoted in pink. These include the subclasses of sub_assembly_component which are floor cassette and roof cassette;

- The overall superclass denoted in blue that supersedes any ontology was simply adopted. This is the *thing* concept denoted in blue.

The outcome of the merged ontology (MO in Figure 6.3) has been adopted in this study because it is more broad-based and encompasses its constituent classifications. This categorisation (panelised system, volumetric system, modular system, hybrid system, solid panel system, composite panel system, and subassembly system) embodies all the other categorisations.

Renewable energy technologies: This is by far the concept with the largest number of sub-concepts. The concept examines energy technologies that deal with energy from renewable sources. In the UK, there is a general consensus within the government and the research community in the use of renewable energy technologies in achieving CO_2 emission targets providing clean energy. But what are renewable energy technologies?

Like in the definition of sustainable development, there is much debate and confusion in terms of which technologies can be classified as renewable. While the term *renewable* energy technology is being used by politicians as a rhetorical propanganda to justify the absolute minimum measures, others such as business developers have used it differently to benefit from government support or grants (Porritt 2005; Warner and Negrete 2005; Marsh 2002). As a result, renewable energy technologies have been classified in at least five different ways in the UK. The Climate Change Levy classification includes energy from waste but excludes large Hydro (MacLeay *et al.*, 2009). The Renewables Obligation classification includes energy from waste under some constraints (only the organic fraction and only using advanced technologies) (MacLeay *et al.*, 2009). The EU definition includes energy from waste with a set of different constraints (waste incineration must not undermine policies to reduce waste and increase recycling) (Toke, 2009). The Energy Saving Trust's Future Energy Scheme classification includes energy from waste with no conditions attached and refurbished large Hydro (Marsh, 2002). The World Wide Fund (WWF) for nature classification excludes barrages from tidal power technology and incineration from municipal waste (Marsh, 2002). Furthermore, WWF does not consider nuclear power to be renewable due to its high risk to the environment and human health associated with its operation. The analysis of the differences of these classifications especially from political and economic perspectives cannot be investigated within the scope of this study. However, on application of the PROMPT methodology of alignment/merging ontologies (Noy and Musen, 2003), a classification which can be considered fundamental and common to all the above classifications (MacLeay *et al.* 2009; Toke 2009; Marsh 2002) and including those of other renowned research establishments such as the BRE and Carbon Trust has been obtained and include the following: *combined heat and power (biomass), geothermal, hydro, solar energy, tidal, wave* and *wind energy systems.*

Building construction materials: These are substances from which construction products, elements or entities may be made (Smith *et al.*, 1997). Based on literature review, the selection of sustainable building materials is often guided by "off-the-shelf" price without the consideration of environmental sustainability (BRE, 2010). In this study environmental sustainability is central to the building materials considered. Many categorisations of sustainable building materials exist depending on the environmental sustainability criteria used (Smith *et al.* 1997; Roaf *et al.* 2001; Chiras 2000). The building materials classification from the Uniclass classification scheme was considered for this study. This is because the scheme incorporates sustainability as well as concepts of energy and environmental issues and supersedes previous classification schemes such as the Construction indexing manual (CI/SfB) and the Common Arrangement of Work Sections (Smith *et al.*, 1997). The top concepts considered are *timber, metal, cementious concrete, natural* and *reconstituted stone, plastics rubber chemical synthetics materials, animal* and *vegetable material.*

Building construction element: A building construction element is a major physical part or system of a building or construction entity which, in itself, or in combination with other elements, fulfils a characteristic predominating functions of the building or other construction entity (Smith *et al.,* 1997). The classification of building construction element by both BRE (2010) and Smith *et al.* (1997) were examined and adopted. BRE is a leading research and consultancy firm working at the forefront of engineering, material science and process management to provide solutions for all aspects of construction from design to end of life, and strategic issues - such as risk management and corporate social responsibility. The top concepts from the synthesis of the above classification systems are *fabric complete element (floors, walls, stair, roof* and *foundation)*; *fabric part of element (carcass* and *openings)* and *fitting furniture equipment (circulation* and *storage)*

Smart system technology: This concept considers building technologies with communication and computing capabilities that can make intelligent decisions in an automated, context-aware and pro-active manner. The sub-concepts treated here are *motion detection, security, video camera monitoring, internet, multi-room audio, telephones, cable and satellite television,* and *vehicle detection technologies.*

Water conservation system: This concept will consider technologies that lead to the optimal exploitation of water in a home, such as *greywater recycling* and *rainwater harvesting.*

Waste minimization technologies: Waste minimization technologies are technologies that are used in reducing or eliminating waste in a building. As reviewed in Chapter 2 the common types are anaerobic digestion, incineration, pyrolysis and gasification.

6.4.2.3 Establishment of the sustainable building technology's related concepts

The last criterion in determining the concepts to be included in the sustainable building technology domain model is the interaction of the sustainable building technology domain model with other knowledge models. In line with the aim of this study (which is that of finding better ways of rendering information about sustainable building technology to professionals) stakeholders' involvement in sustainable building technology becomes imperative. Firstly, it is important to know who are the different stakeholders involved, such as suppliers, installers, researchers, developers. This will be captured using the *organisation* concept. Secondly, it is important to know on which structures the sustainable building technologies can be incorporated. The logical choice is any building (or building for short). Thus, another key concept in the domain of sustainable building technology is the *building* concept. Thirdly, it is important to know about the appliances that will consume the natural resources provided by the sustainable building technologies. This is captured as *household appliance* concept. Building knowledge models about these concepts can be undertaken through the use of existing knowledge models or redesigning from scratch. Concepts were abstracted to form documents which were enriched to build up the organisation, building and household appliance concepts. The *organisation, building,* and *household appliance* concepts will be examined in the ensuing paragraphs.

Organisation: The *organisation* concept adopted in this study has been well researched in the TOVE project (Grüninger and Fox, 1995) where an organisation is considered as an agent that plays one or more roles (Grüninger and Fox 1995; Fox *et al.* 1996; Fox and Grüninger 1994). In the case of this study, the *organisation* concept defines the key actors involved in the sustainable building technology domain. For example, installers, suppliers and developers are sub-concepts to be considered under the *organisation* concept.

Building: The *building* concept defines the physical space in which the sustainable building technologies are being applied. The *building* concept was extracted from the IFC developed by buildingSmart (IAI, 2010). This concept is a component of the core IFC. The main reason for considering the *building* concept from IFC was its richness in some data-type properties which were suitable for application in the sustainable building technology domain. These properties are *roofType, hasRoofType, buildingParts* and the *buildingAddress*.

Household appliance: The household appliance captures knowledge about the various domestic energy appliances in the UK houses. It has four main sub-concepts, the *cold, wet, brown* and *cooking* energy appliances. This classification has been adopted from Firth *et al.* (2008), Wood and Newborough (2007) and Market Transformation Programme (2010) which are the most current and elaborate studies on domestic energy appliances in the UK housing sector. The *cold* category is a group of appliances that are continuously switched on and power consumption cycles between zero and a set power level. The *brown* category is a group of appliances that are actively switched on by householders. When these appliances are not in use the power consumption may be non-zero. The *cooking* category is a group of appliances that are actively switched on by householders. When they are not in use, the power consumption is zero. Furthermore, cooking category comprises electrical cooking equipment only. The *wet* category is similar to the cooking category but does not include electrical cooking equipment. Some examples of the sub-concepts of the *cold* concept are refrigerators and freezers; *brown* are mobile phone chargers and television; *wet* are tumble dryers and dish washers; *cooking* are boiling kettles and electrical ovens.

Having examined the main concepts to be included in the sustainable building domain, it becomes imperative to assemble these concepts together in order to establish some basic hierarchical relations between them. A key recommendation in Gómez-Pérez *et al.* (2004) and the PROMPT methodology (Noy and Musen, 2003) is that if two or more concepts exist with no relation, a superclass can be created to include the independent sub-concepts. On application of this recommendation five new concepts will be introduced. The concepts are *thing, building construction technology, building construction systems, resource efficient technology* and *building construction technology.*

The concept *thing* is a generic concept used in ontology development in representing both tangible and intangible concepts (Noy and McGuinness, 2001). The *thing* concept can be used at any level in an ontology hierarchy (Noy and McGuinness, 2001). *Building construction technology* includes building construction element, building construction material, building construction system, resource efficient technology, and renewable energy technology. *Building construction system* will include traditional and modern methods of construction. *Resource efficient technology* will include smart system, water conservation and waste minimisation technologies. The different knowledge objects about the sustainable building technology domain can be represented in a class diagram as shown in Figure 6.4 below.

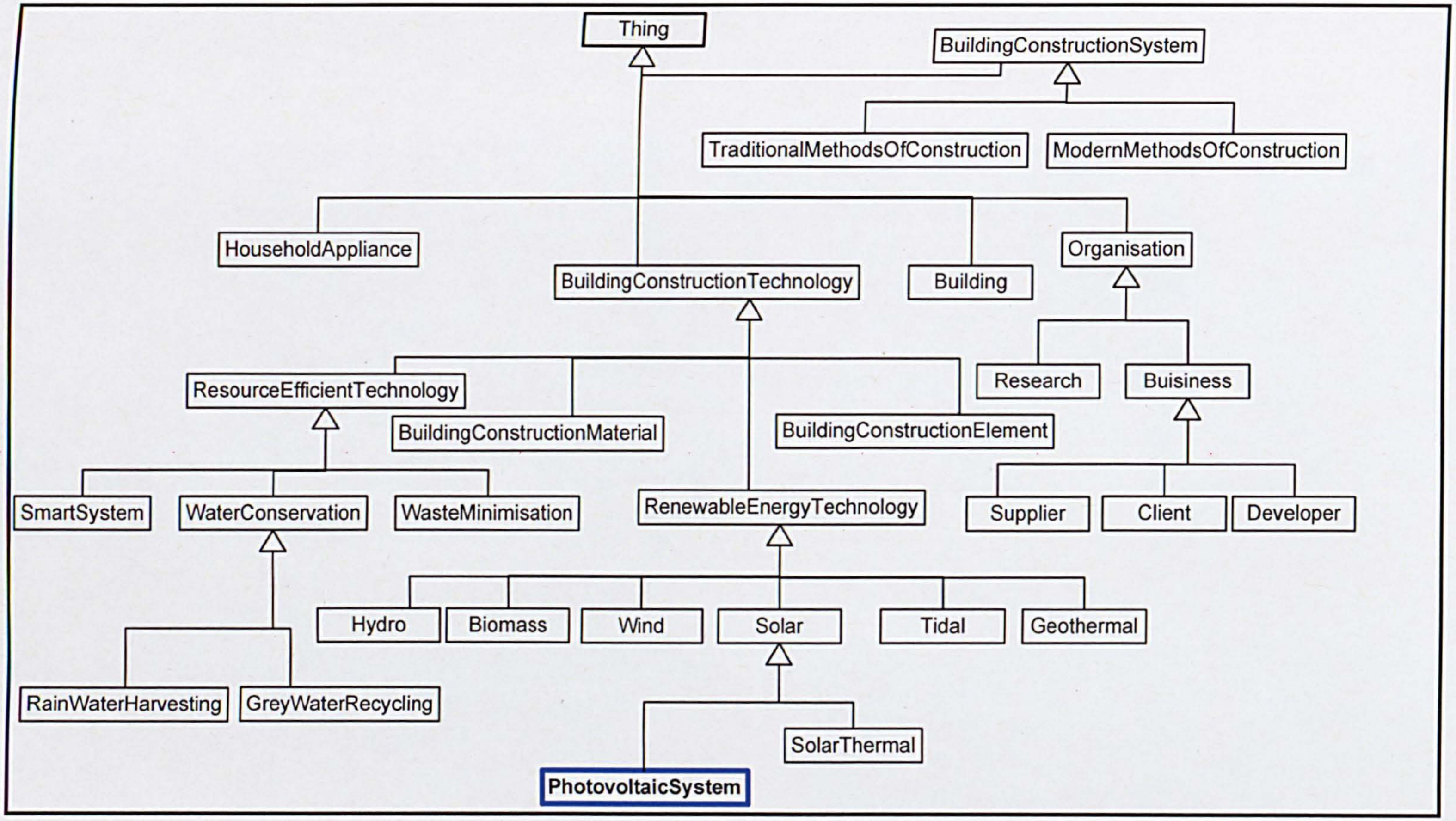

Figure 6.4. Partial hierarchical representation of concepts of the sustainable building technology domain

Figure 6.4 is a presentation of the top concepts in the domain of sustainable building technology. This is only a partial conceptualisation of the domain of sustainable building technology. In order to completely specify this model, object and data-type properties are required. This will be examined in section 6.4.3.

6.4.3 Complete construction of the sustainable building technology domain schema

6.4.3.1 Determination of annotation properties

Annotation properties are used in adding information to classes, individuals and/or object/data properties, e.g. information such as the number of instances in a class, the literature source from which the class was obtained from. The Protégé-OWL editor provides a simplified way of capturing and tagging annotation properties onto the different ontological components. Hence, the annotation properties will be added using Protégé-OWL ontology editor during the implementation stage discussed in Chapter 7.

6.4.3.2 Determination of object properties

Object properties describe the relations between concepts and consequently between instances of the concepts. For instance, what role does the *organisation* concept play on the *building construction technology* domain concept? What relationship exists between the *household appliance* concept and the *building* concept? These questions can be answered by establishing the role a concept plays on another. An organisation such as a *research organisation* will be researching about a given renewable energy technology. In this case an object property *researchesAbout* can be used to connect the *organisation* and the *building construction technology* concept. This can be done as follows: "A research organisation *researchesAbout* a building construction technology". Given that the *organisation* concept has subclasses such as business organisation; its object properties will be different. For instance, a supplier *supplies*, while an installer *installs* a given building construction technology. Hence, object properties like *supplies* and *installs* can also link the subclasses of the *organisation* concept to the *building construction technology* concept. Some object properties may obey inheritance. The object property *isInvolvedIn* is used to define the different activities; an *organisation* participates in with regards to a *building construction technology*. Hence, *isInvolvedIn* is the main object property relating *organisation* to *building construction technology*. The relationship is read as "An *organisation isInvolvedIn* a *building construction technology*". The object property *isInvolvedIn* has sub-properties, *researchesAbout, installs, supplies*, etc. In a like manner, in the latter, a connection can be created as "A building *hasContent* household appliances". Object properties can also have inverses, for example, the inverse of *researchesAbout* can be *isResearchedBy*. In the organisation-building construction technology relationship, a research institute (i.e. subclass of an organisation) may be undertaking research on building construction technology. This can be formulated as "building construction technology *isResearchedBy* a research institute". The main object properties involved in the domain of sustainable building technology domain is presented in Figure 6.5, depicting the top concepts. The sub-properties have not been indicated but will be captured in the final model when edited in an ontology editor.

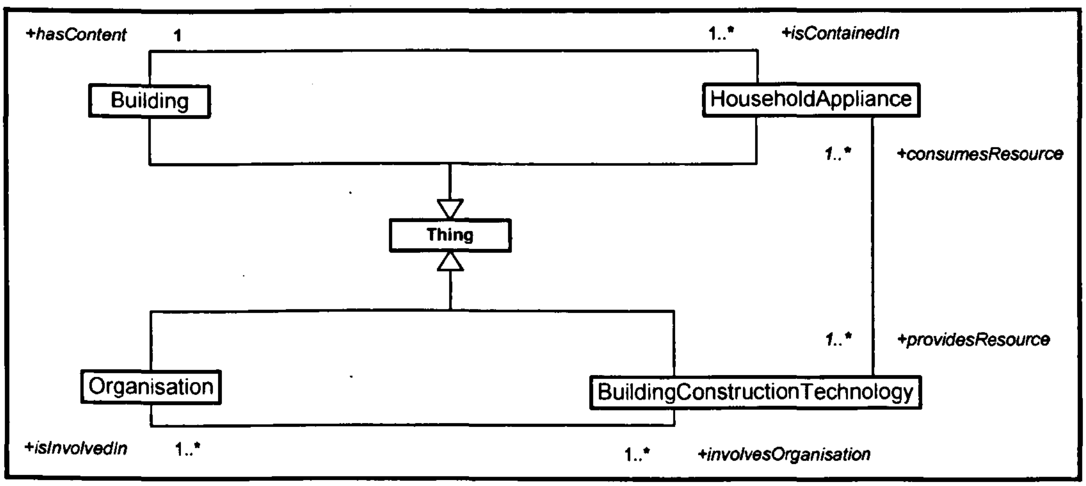

Figure 6.5. Top-level concepts of sustainable building technology domain involving object properties

Figure 6.5 depicts the relationship (using object properties) between the top level concepts of the sustainable building technology domain. It is also important to characterise these concepts by using specific attributes that differentiate each concept from the other.

6.4.3.3 Determination of data properties

Just like in object-oriented programming, where attributes define the properties of an object or class, data-type properties are used in describing properties of concepts in a knowledge model. Considering the case of the *organisation* concept, a data-type property could be *hasAddress* often formulated as "An organisation *hasAddress* 53 Masons' Road. A data-type property has a value type (string, integer, boolean, etc.) and a value. In this study, data-type properties will contribute greatly as criteria for making informed decisions (e.g. selecting an appropriate sustainable building technology to be incorporated in a building project) about the domain of sustainable building technology domain. Data values will serve in comparing and selecting the different sustainable building technologies and/or different organisations involved in each technology. For example, data-type properties can be used in selecting the most reliable supplier. Sustainable building performance data can be used as data properties in the selection of alternative technologies. However, there is a lack of an extensive integrated performance framework in the literature that can be used in the assessment of sustainable building technologies (Nelms *et al.*, 2007). The challenge has been to establish one in this study. The framework developed here benefitted from the works of GBL (2010), Nelms *et al.* (2005: 2007) and Becker (2002). Nelms *et al.* (2005: 2007) provide a logical structure for the assessment of a particular technology with regards to sustainability concepts, performance, and relevance to construction projects. Becker (2002) developed a performance framework for assessing innovative building systems. The integration took into consideration the performance indicators developed by BREEAM. The methodology proposed by Noy and Musen (2003) was used to semantically aggregate the data-type properties (see Table 6.1). However, as the PV-system is the focus of this study, the values of the data-type properties would not be included. The data-types developed are applicable only to the building construction technology where the PV-system is a subconcept

Table 6.1. Data-type properties for building construction technology

	Criteria	Description
Environmental	Annual CO_2 emissions	Annual quantity of CO_2 emissions from a given building construction technology
	Annual CO_2 gas savings	Annual quantity of CO_2 gases saved when a given building construction technology is used
	Solid waste generation	Amount of sold waste generated during the operational phase of a given building construction technology
Social	Visual impact	These are flickering shadows that may be a nuisance for neighbouring properties from building construction technologies
	Noise impact	This is the noise generated from operating the given building construction technology
	Risk to human health	These are health risk associated with the emission of toxic materials, e.g. mercury
Economic	Capital cost	This is the total cost needed to bring a building construction technology project to an operable status
	Life cycle cost	This is the total life time cost of any given building construction technology
	Maintenance cost	Cost of labour and parts to perform repairs during the operational phase of building construction technologies
	Operational cost	This is the cost required to run a given building construction technology
	Installation cost	This is the cost required to installed a given building construction technology
	Annual cost saving	This is the cost or financial gained from using building construction technology compared to a non-renewable source
	Warranty	This is a collateral assurance from manufacturer that ensures a given technology will be repaired if something should malfunction during a given period often called "warranty period"
	Reliability	The quality level at which one can depend on the energy supply from building construction technology source
	Durability	This refers to the long-term success of a given building construction technology and/or its components
	Adaptability	The ease with which a given building construction technology can be integrated to the natural terrain
	Expected lifetime	This is the predicted service life of a given building construction technology
Physical	Weight	This refers to the magnitude of a force on a given technology with respect the gravitational pull
	Usable space	Amount of space occupied by a given building construction technology during its installation and operation

To complete the knowledge specification the data-type properties of the concepts - the building, the organisation and the household appliance are required. Since the *building, organisation* and *household appliance* have been re-used, they have been enriched with some data-type properties to reflect each domain.

Incorporating the above properties into partial knowledge model of Figure 6.5, the complete knowledge model of the sustainable building technology domain is presented in Figure 6.6.

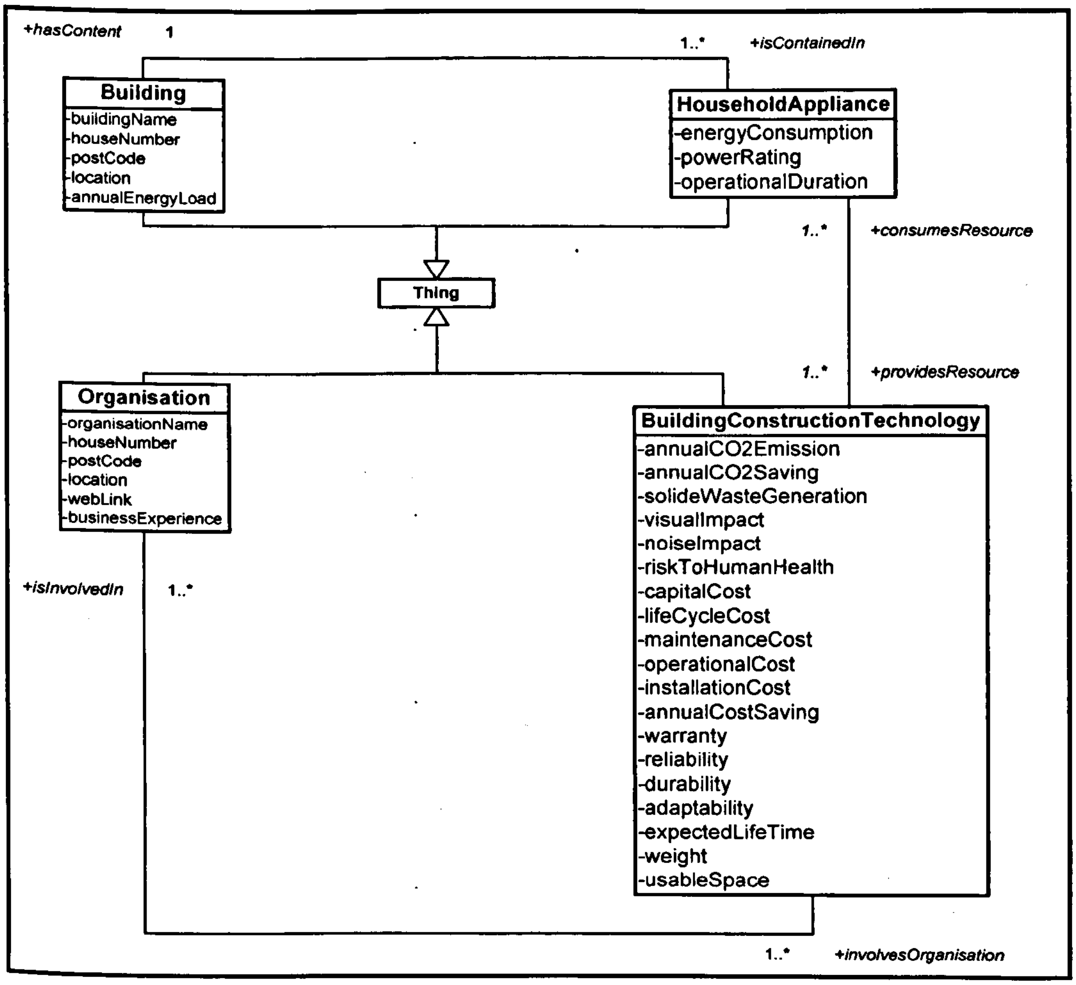

Figure 6.6. Complete conceptual model of sustainable building technology

At this stage the sustainable building knowledge model is complete to a large extent excluding instances and values for data-type properties. Instances and data values are concepts that depend on suppliers. Most knowledge engineering tools (Protégé-OWL in the case of this study) have place-holders for instances and data-values. The place-holders are directly linked to the domain knowledge model. In the ensuing section populating the knowledge model with instances will be examined.

6.5 Knowledge refinement of sustainable building technology

As stated in the methodological framework in Chapter 5 the two main activities in this stage are the verification (semantic and syntactic) and population of the knowledge model with instances. By pursuing the PROMPT methodology, the semantic verification of the knowledge model was guaranteed. Syntactic verification is best done with the use of knowledge verification tools in a software environment. Syntactic verification will be undertaken during the implementation phase in Chapter 7. Furthermore, as explained in the methodology in Chapter 5, it will be quicker and appropriate to populate the knowledge model in a software environment. However, the population of instances in a software environment will only be applicable to the PV-system as it is the focus of this study. This will be examined in Chapter 7.

6.6 Conceptual modelling of PV-system

After an overview of the PV-system, the first two phases of the CommonKADS methodology, i.e. knowledge identification and specification are implemented to generate the partial PV-system domain knowledge model. However, because the major purpose of developing a PV-system knowledge model is to further extend the PV-system domain knowledge to include the selection and design applications, it was necessary to include concepts that can deal with them. This requires the establishment of knowledge requirements that can facilitate the selection and design of PV-systems. In order to establish the ontology requirements, literature on PV-systems from various sources was consulted. Furthermore, informal discussions with manufucturers of PV-systems were held. The outcome of this activity led to the establishment of a process model (Figure 6.7) that depicts the information and steps that facilitate the selection, acquisition and the design of PV-systems (see Tah and Abanda, 2011). This process model provided the opportunity to establish how certain entities could be modelled. Furthermore, the strength of the process model lies in its ability to capture operations such as calculation of the size of PV-system modules that would not have been possible to capture in the normal knowledge elicitation process of ontology development. This is particularly suitable in ontology application development.

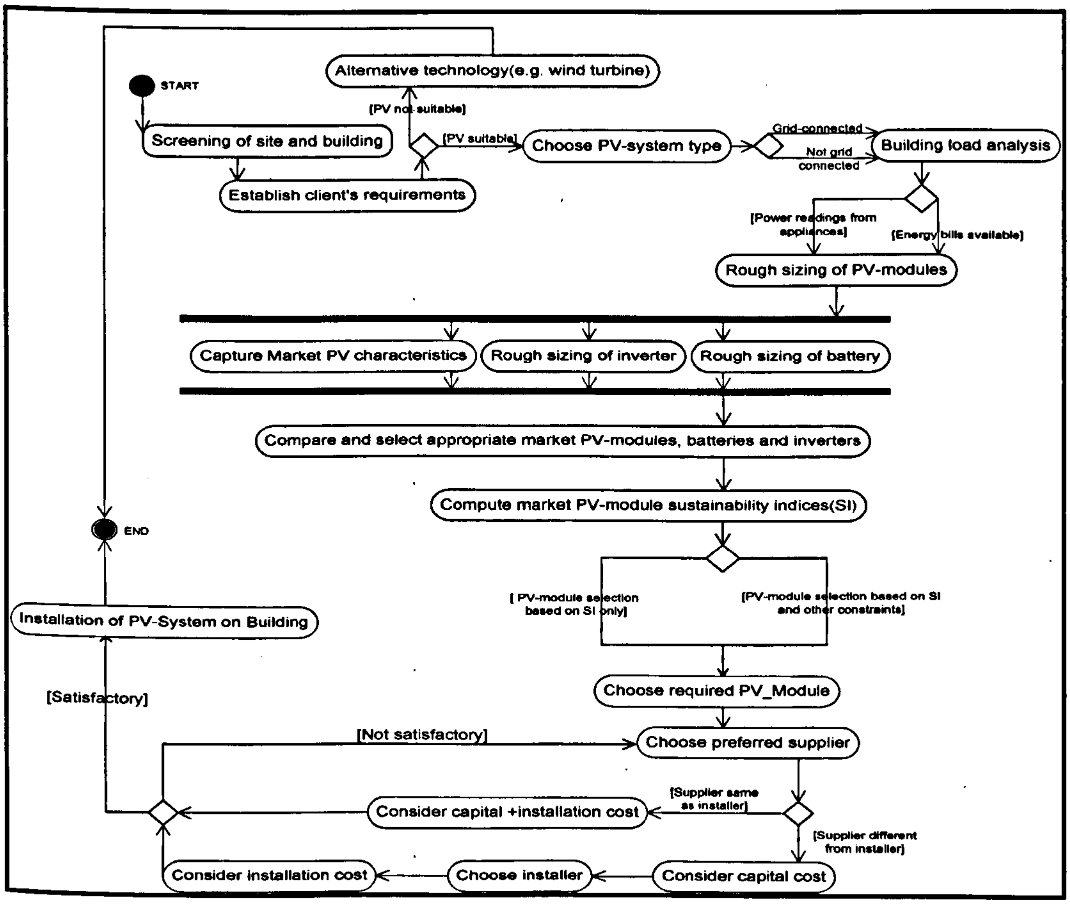

Figure 6.7. Process model for the selection and design of PV-system
[Source: (Tah and Abanda, 2011)]

The process model in Figure 6.7 laid the foundation for the establishment of two ontological components which are key to the PV-system ontology. These are the key ontological classes and the potential types of the different classes' attributes. However, there are some challenges such as: which entities should be modelled as "first class objects", subclasses or dependents on some objects? For example, should the supplier's class be modelled as a supplier class or should it be included under a more generic class such as an organization class? What are the types of relationships between the classes? For example, what is the relationship between a client and a supplier?

The UML was used to create a semantically rich class diagram to facilitate a graphical representation and visualisation of the concepts and relationships between them. The class diagram is depicted in Figure 6.8. The class diagram depicts four top level concepts which include the PhotovoltaicSystem, Building, Organisation and the HouseholdAppliance.

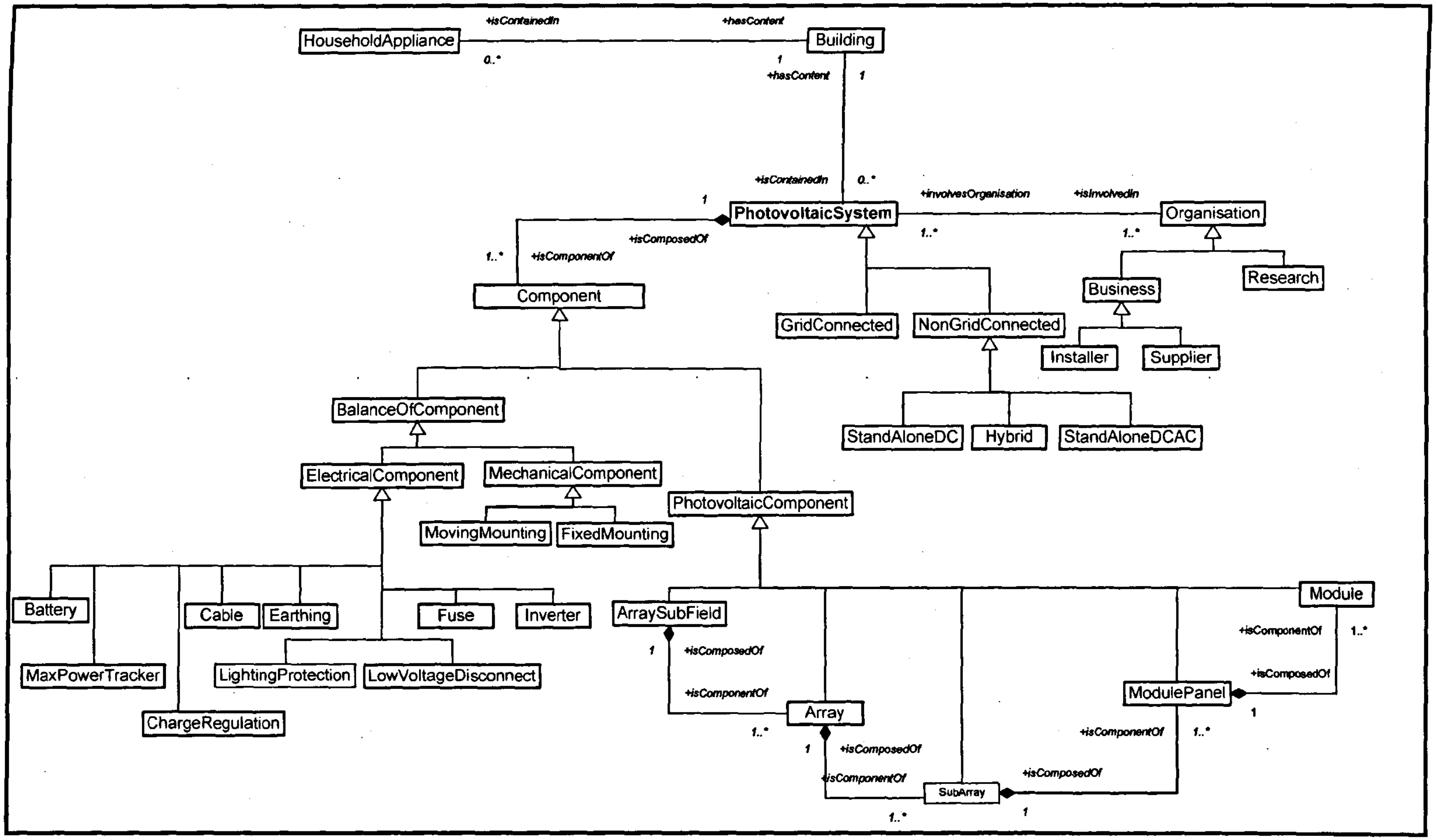

Figure 6.8. Concepts of PV-system domain involving object properties

In order to completely specify, by implementing the last phase of the CommonKADS methodology (knowledge refinement), the PV-system domain knowledge, instances and properties were included in the partial PV-system knowledge model presented in Figure 6.8. The instances were manually extracted from companies' websites or product list stored in the Green Book Live database (GBL, 2010). Green Book Live is a free online database designed by BRE which can help specifiers and end users identify products and services that can help to reduce their impact on the environment. Based on the fact that the PV-system domain is a sub-concept of the sustainable building technology domain, it inherited the object and data properties. Annotation properties were incorporated in specific cases with regards to PV-system technology. Given that the data-type properties have been established for the sustainable building technology domain and that the concept of inheritance between classes and subclasses holds, the same data-type properties for the building construction technology in Table 6.1 applies to the PV-system domain. This will be incorporated in PV-system conceptual model in Figure 6.9. From the analysis of the Green Book Live database, many other sub-concepts including data-type properties that were not captured during the conceptualisation of sustainable building technologies, were discovered. In analysing the different concepts including properties of PV-systems, some semantic problems were encountered. Like in the case of sustainable building technologies, 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-modules were assigned with the same code as nominal power output which 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-module properties than others. Thus, it was imperative to semantically validate the captured properties concepts extracted from the Green Book Live database. The technique of Noy and Musen (2003) was employed. The following example illustrates a case where two suppliers specified differently a PV-array. 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 Noy and Musen (2003), 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 implementing the techniques of Noy and Musen (2003), a semantically rich knowledge constructs relating ontology components of the PV-system was developed. However, due to the huge number of the different properties involved in each PV component, only the properties captured by the top concepts, i.e. *building, organisation, household appliance*, and *photovoltaic system* will be shown below in Figure 6.9. For the purpose of this study, PV-module, a sub-component which will play a key role in the selection of a PV-system will be represented.

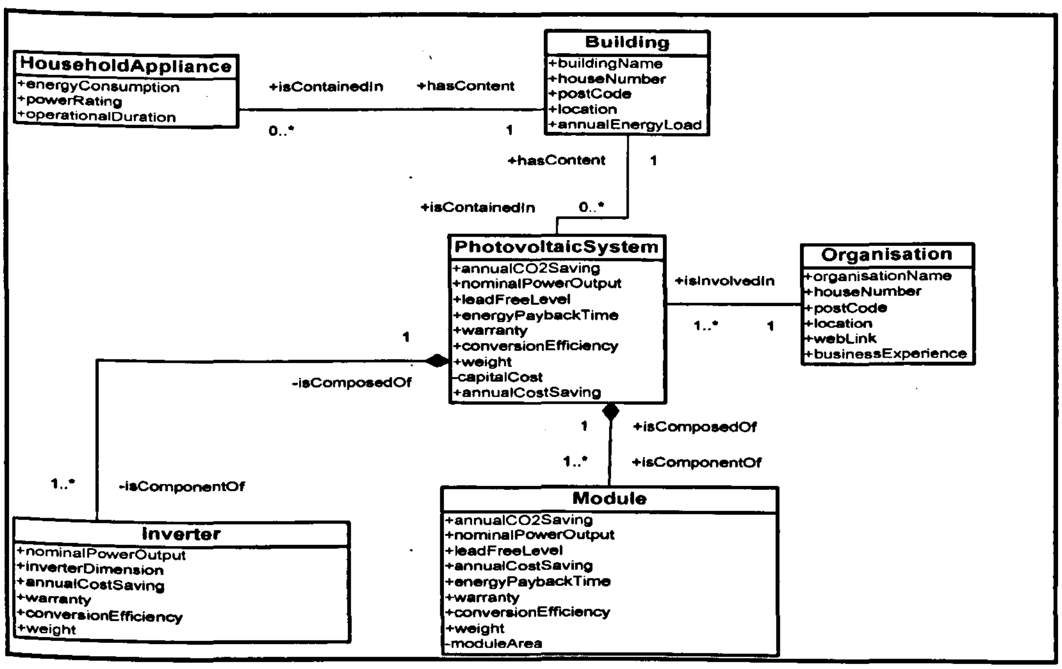

Figure 6.9. Top level concepts of the PV-system ontology

6.7 Populating the PV-system ontology with instances

Instances represent objects in the domain of interest. For instance, PV-MF110EC4$_{110Wp}$ is an instance of the PV-system class with concrete specifications designed by Mitsubishi Electric (MTE, 2010). Other instances include the different suppliers and installers of photovoltaic systems. In this study, instances have been extracted from the Green Book Live database. In cases where there are no databases; independent variables generated automatically by knowledge modelling software will be used. The variables will prompt users to edit attribute values. Based on the huge size of the number of instances in the database, a representative snapshot will be presented. The snapshot is achieved through the use of Protégé-OWL editor in Chapter 7.

Two main challenges that emerged from the extraction of instances was the existence of different units for the different values of the data-type properties and the fact that the data-types were not aggregated. It was imperative to aggregate the data-type properties and harmonise the units so that a comparative analysis could be made. For instance, the grouping of economic, social, environmental, technical and physical data-type properties as independent categories can facilitate comparison between the different categories with respect to the different ontology instances. An immediate consequence is that a sustainability appraisal of the PV-system can easily be made. Another major advantage of aggregating data-type properties is to minimise the occurrences of anomalies and hence minimising the task of syntactic verification of the knowledge model during implementation in a software environment. For instance, by aggregating all the economic criteria as a single economic index, many different units for the different criteria are avoided. It is therefore imperative to demonstrate how the data-type properties of the PV-system were aggregated. The methodology proposed by Krajnc and Glavič (2005a:2005b) was used. This methodology is very suitable for integrating sustainability indices and is used in this study.

6.8 Aggregation of the data-type properties into a composite sustainability index

In order to develop the mathematical models for computing the composite index, it is important to state the decision problem that the composite index will solve. In decision-making processes a facilitator will seek audience with decision makers to structure the problem which is often divided into three main parts: the goal (buy a PV-system), criteria (cost, efficiency, pay-back period, warranty, etc.) and alternatives (PV1, PV2, etc.). The framework for such a problem is presented in Figure 6.10.

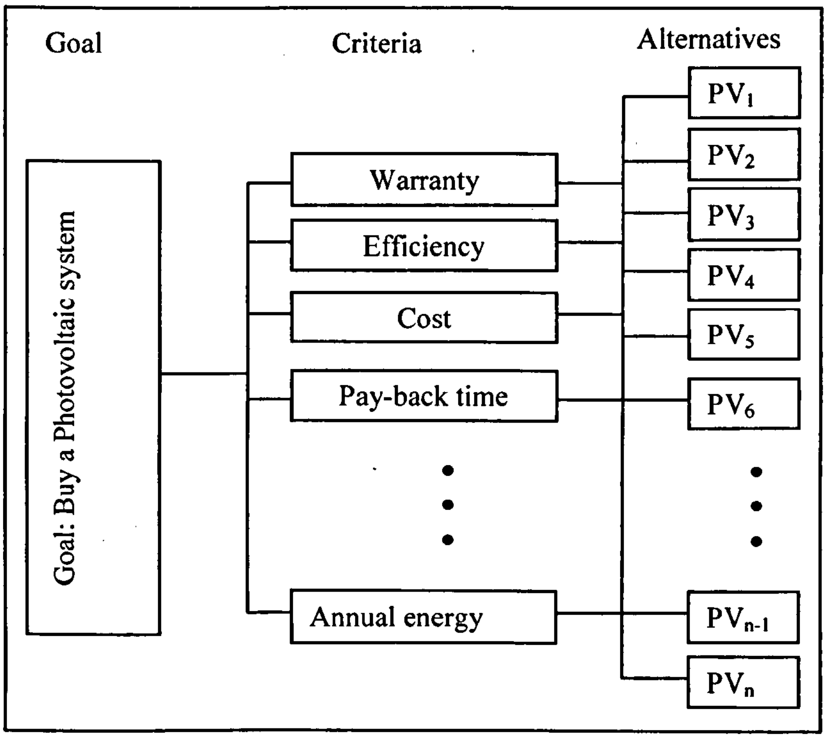

Figure 6.10. Decomposition of a multi-criteria problem into a hierarchy

The challenges in establishing the criteria are grouping them to belong to a given category, attributing qualitative or quantitative values. The situation is further exacerbated by the fact that most company data about their PV-system products are published in different units. This makes it difficult to compare two PV-systems with the same or different parameters. There is need to bring the data values to a common scale. To achieve this, a framework developed based on methodologies for the normalisation of data for use in selecting products and suppliers in Krajnc and Glavič (2005a) is presented below in Figure 6.11.

Figure 6.11. Framework for determining values for data-type properties

From the above framework, the computation of the composite sustainable index consists of seven main steps. These are the establishment of indicators, the grouping of indicators, the categorisation (judging) of indicators into positive and negative indicators, the weighting of indicators, the normalisation of indicators, the calculation of sub-indices and the combination of sub-indices to obtain the composite sustainable index.

Step 1: Establishment of sustainable indicators

Although this activity has been implicitly undertaken during the knowledge acquisition process and ontology development process, it is necessary to relate them to the concepts of sustainability indicators as a basis for the selection of PV-systems. In this stage the criteria or indicators that reflect environmental impacts are selected. The list of criteria should be sufficiently precise and comprehensive to cover a full range of issues that can be used in making a realistic judgement between the alternatives. The decision model should focus on the aspects that are salient and eliminate those that are not attractive.

Step 2: Grouping the selected indicators

The indicators should be grouped according to the different assessment criteria for selecting a given technology. Selected indicators should be grouped according to the main aspects of sustainability, i.e. environmental (j=1), social (j=2) and economic (j=3). These groups have been chosen because they constitute the back-bone of the widely acknowledged definition of sustainable development (Elkington, 1998).

The economic group of indicators concerns the impacts of PV-system on the financial viability of the stakeholders involved. The environmental group of indicators cover impacts of PV-system on the environment, including ecosystems, land, air and water. Societal group of indicators reflects the rapport between the PV-systems' suppliers and the clients. An example of a societal indicator is the client's reliability on the business experience. Can a client rely on the fact that an experienced supplier will provide a PV-system in good conditions?

Step 3: Judging the indicators

The indicators, i identified and classified under groups j, are categorised as positive and negative indicators with respect to sustainability. A positive indicator is defined as a criterion whose increasing value has a positive impact on sustainable development while a negative indicator is a criterion whose increasing value has a negative impact on sustainable development with respect to a client who is interested in investing in a PV-system.

Step 4: Weighting the indicators

In any list of indicators or criteria, some are likely to be more important than others. For instance, in assessing a PV-system, energy saving may be more important than the visual impact. In appraisal of different PV-systems, choosing an option from a list of alternatives means that priorities must be set and weights assigned to each criterion's priority. In practice, the weights are determined by a human decision maker who is abreast with professional experience and knowledge in the application area or through a survey where experts' opinion are captured. These methods are often time consuming, subjective and expensive (Hobbs and Meier, 2000) and hence out of scope of this study. However, studies about supplier and product selection based on a survey of 273 purchasing managers revealed that quality was the most perceived criteria (Talluri and Narasimhan, 2003). For the purposes of this study, and given the fact that the aim of a client is to select a PV-system with the most sustainability credentials, environmental quality will be attributed with the highest weight. Then, economic criterion will be attributed the second highest weight as it is directly related to environmental quality. Social criterion will occupy the third position and other criteria will be attributed different weights but less than those of environmental quality, economic and social criteria. In the literature different assumptions can be made about the different weights and most often equal weights are used to ease computation. However, we have used different weights so that clarity in the computational steps can easily be noticed. Furthermore, the established weights will be aggregated using a methodology for the integration of sustainability indices developed by Krajnc and Glavič (2005a; 2005b). The method is briefly introduced below to highlight its applicability and suitability in the context of sustainability assessment.

Let us assume that N indicators of sustainability are being considered with the goal of computing relative weights of each indicator with respect to all the other indicators of group j. This is done by pair-wise comparisons between each pair of indicators. The comparisons are made by posing the question which of the two indicators i and k is more important with respect to sustainability credentials, respectively. The intensity of preference is expressed on a factor scale from 1 to 9. The values of 1-9 adopted from Hafeez *et al.* (2002) are defined in Table 6.2.

Table 6.2. Comparison scale of analytic hierarchy process

Factor of preference, *p*	Definition
1	Equal importance
3	Moderate importance of one over another
5	Strong or essential of one over another
7	Very strong or demonstrated importance of one over another
9	Extreme importance of one over another
2,4,6,8	Intermediate values
Reciprocal 1/*p*	Reciprocal for inverse comparison

These pair-wise comparisons result in a (*NxN*) positive reciprocal matrix *A*, where the leading diagonal a_{ik}=1 and reciprocal property a_{ki} = ($1/a_{ik}$), *i*, *k*=1... *n* assuming: if indicator *i* is '*p*-times' the importance of indicator *k*, then, necessarily, indicator *k* is '1/*p*-times' the importance of indicator *i*. The normalized weight of each indicator is determined by dividing the indicator's relative weight by the sum of relative weights in i^{th} column, and then averaging the values across the corresponding k^{th} rows (*i* representing the criteria of an object *k*); this average in the column is the normalized weight vector *W* containing weights (W_{ji}) of sustainability indicators selected.

Step 5: Normalising the indicators

A major challenge in aggregating indicators into the sustainability index (S_I) is the fact that indicators may be expressed in different units. It therefore requires normalisation for it to be suitable for aggregation. The following mathematical models (Hersh 2006; Krajnc and Glavič 2005a) are often used for normalising indicators. The normalised indicators are often classified as type "more is better" and "less is better". An example of a "more is better" type indicator with respect to a client interested in a PV-system is the energy efficiency of the PV-system. An example of a "less is better" type indicator with respect to a client interested in a PV-system is capital cost of the PV-system. The mathematical models used in normalising indicators of type "more is better" and "less is better" are presented in equations 6.1 and 6.2.

Equation 6.1. Normalised indicator of type "more is better"

$$I^{+}_{N,ij} = \frac{I^{+}_{A,ij} - I^{+}_{\min,j}}{I^{+}_{\max,j} - I^{+}_{\min,j}} \qquad 6.1$$

Equation 6.2. Normalised indicator of type "less is better"

$$I^{-}_{N,ij} = 1 - \frac{I^{-}_{A,ij} - I^{-}_{\min,j}}{I^{-}_{\max,j} - I^{-}_{\min,j}} \qquad 6.2$$

Where :

$I^{+}_{N,ij}$ is the normalised indicator *i* of type "more is better" for group indicators *j;*

$I^{-}_{N,ij}$ is the normalised indicator *i* of type "less is better" for group of indicators *j;*

$I^{+}_{A,ij}$ is the A^th^ matrix entry for the indicator ***i*** of type "more is better" for group indicators *j;*

$I^{+}_{\max,j}$ is the maximum of the matrix entries for the indicator ***i*** of type "more is better" for group indicators *j;*

$I^{+}_{\min,j}$ is the minimum of the matrix entries for the indicator ***i*** of type "more is better" for group indicators *j;*

$I^{-}_{A,ij}$ is the A^th^ matrix entry for the indicator ***i*** of type "less is better" for group indicators *j;*

$I^{-}_{\max,j}$ is the maximum of the matrix entries for the indicator ***i*** of type "less is better" for group indicators *j;*

$I^{-}_{\min,j}$ is the minimum of the matrix entries for the indicator ***i*** of type "less is better" for group indicators *j.*

By using equations 6.1 and 6.2, it is now possible to incorporate different kinds of quantities with different units of measurement. One main advantage of the proposed normalisation of indicators is the clear compatibility of different indicators.

Step 6: Calculating the sub-indices

Having normalised the indicators using equations 6.1 and 6.2, the computation of S_I becomes a step-by-step process of grouping various basic indicators into the sustainability sub-index ($S_{I,j}$). This grouping exercise is conducted for each group of sustainability indicators j. Sub-indices can be derived using equation 6.3.

Equation 6.3. Sustainability sub-index for a group of indicators

$$I_{S,j} = \sum_{ji}^{n} W_{ji} \cdot I^{+}_{N,ji} + \sum_{ji}^{n} W_{ji} \cdot I^{-}_{N,ji} \qquad 6.3$$

To establish the likelihood of the correctness of the computed weight of indicators, two conditions are verified. Firstly, that each of the average weights of the indicators of a group of indicators should always be positive. Secondly, the sum of all the weights of indicators should be equal to unity. This is mathematically modelled as in equation 6.4.

Equation 6.4. Weight of indicators

$$W_{ji} \geq 0, \sum_{ji}^{n} W_{ji} = 1, \qquad 6.4$$

Where $S_{I,j}$ is the sustainability sub-index for a group of indicators j. W_{ji} is the weight of indicator i for the group of sustainability indicators j and reflects the importance of this indicator in the sustainability assessment.

Step 7: Combining the sub-indices into the S_I

The sustainability sub-indices are combined into the composite sustainability index, S_I as in equation 6.5.

Equation 6.5. Composite sustainability index

$$S_I = \sum_{j}^{n} W_j \cdot I_{s,j} \qquad 6.5$$

W_j denotes the factor representing a priori weight given to the group j of sustainability indicators. These weights should reflect priorities in the opinion of decision makers. The weights reflect the importance accorded to the environmental, economic, social, technical and physical performance of the PV-system product.

The above steps will be implemented in the treatment of data obtained from the Green Book Live database. The Green Book Live database was critically examined and fact sheets provided by the different UK PV-system suppliers provided data such as peak power or nominal power output, lead free level, business experience, energy payback time, product warranty, conversion efficiency, weight and module area. It was realised that most suppliers do not provide cost information and the amount of greenhouse gases saved by using a particular PV-system technology. Hence, the list of data or criteria was extended to include annual CO_2 savings, capital cost of a PV-array, and an annual cost saving when using a given PV-module. These criteria were classified into the environmental, social, economic, technical and physical dimensions and presented in Table 6.3. The PV-system assessment criteria contain fewer criteria than the generic framework for assessing sustainable building technologies examined in Table 6.1. This is because the criteria for assessing the former were abstracted from Green Book Live only where complete data values for most of the data-type properties were available and the criteria for the latter were abstracted from a number of sources including Nelms *et al.* (2005: 2007), Becker (2002) and Green Book Live (GBL, 2010).

Table 6.3. Data-type properties for the PV-system domain

	Code	Criteria	Unit
Environmental	E1	Annual CO_2 saving	$kgCO_2/annum/m^2$
	E2	Nominal power output	Watt
	E3	Lead free level	%
Social	S1	business experience	years
Economic	F1	Capital cost	£
	F2	Annual cost saving	£
	F3	Energy payback time	years
	F4	Warranty	years
Technical	T1	Conversion efficiency	%
Physical	P1	Module weight	Kg
	P2	Module area	m^2

Given that this research is about investigating the suitability of a new web technology, rather than mine data from all the available companies from the Green Book Live database, 4 companies that provided a comprehensive real data were chosen for illustrative purposes. These companies will be designated Company 1, 2, 3, and 4. The different data associated with the PV-modules of these companies are denoted as M1 belongs to Company 1, M2 and M3 belong to Company 2, M4, M5 and M6 belong to Company 3, M7 and M8 belong to Company 4. Furthermore, because of the importance of the cost and CO_2 emission criteria of sustainable building technologies and PV-systems, estimated data values from different literature sources other than the Green Book Live were used for the annual CO_2 savings, capital cost and annual cost savings criteria. The criteria and data are presented in Table 6.4.

Table 6.4. Decision matrix for the selection of PV-systems

			Company1	Company 2		Company 3			Company 4	
		Units	M1	M2	M3	M4	M5	M6	M7	M8
Environmental indicators										
Annual CO_2 saving	E1	$KgCO_2$	1300*	1100*	1000*	1290*	1000*	800*	950*	900*
Peak power or nominal output	E2	Watt	185	65	60	185	170	80	130	115
Lead free level	E3	%	0	0	0	0	0	0	100	100
Social indicators										
Business experience	S1	Years	12	30	30	50	50	50	35	35
Economic indicators										
Capital cost	F1	£	9000*	8000*	6500*	8800*	7500*	5000*	6500*	6700*
Annual cost saving	F2	£	400*	300*	200*	355*	200*	150*	215*	190*
Energy payback time	F3	Years	8	8	8	8	2	3	2	2
Warranty	F4	Years	25	25	25	20	20	20	25	25
Technical indicators										
Conversion efficiency	T1	%	14.7	12	11	14.1	13	7.6	12.9	11.4
Physical indicators										
Weight	P1	Kg	14.5	6.5	3.5	16	16	18	13	13.5
Module area	P2	m^2	1.26	0.47	0.47	1.31	1.31	1.05	1.01	1.01

*Data estimated from other literature sources other than the Green Book Live database

The above criteria are now grouped into both the positive and negative indicators as in Table 6.5.

Table 6.5. Grouping the indicators into positive and negative performance

	Positive indicators	Negative indicators
Environmental	E1, E2, E3	
Social	S1	
Economic	F2, F4	F1, F3
Technical	T1	
Physical		P1, P2

From Table 6.5, F1, F3, P1 and P2 have been classified as negative indicators. One of the barriers to the uptake of sustainable building technologies in general has been a high cost associated with these technologies. Increasing the capital cost and energy payback time will constitute a barrier and hence a negative indicator from the perspective of a client. With respect to P1 and P2 i.e. the weight and module area respectively, increasing these parameters will entail additional weight and more space from the building of a client. Increasing the weight of the module might translate to structurally redesigning of some structures of the buildings. This often translates to an increase in cost which is a negative barrier. The challenge on increasing the module area might be the fact that the roof top cannot be modified. This constitutes a constraint and thus considered a negative indicator.

After classifying the criteria into both positive and negative indicators, the indicators are graded according to the AHP pair-wise comparison scale in Table 6.2. The data values are further normalised using equations 6.1 and 6.2 and the results presented in Tables 6.6, 6.7, 6.8, 6.9, 6.10 and 6.11. In order to provide clarity in the computation, a detail analysis will be provided about the values presented in Table 6.6 and only the final results will be presented in Tables 6.7, 6.8, 6.9 and 6.10.

The first step in the estimation of the weights of indicators is to attribute a level of importance on the different indicators using the AHR pair-wise comparison technique. We will assume that: the *peak power output* (E2) is 4 times more important than the *annual CO_2 saving* (E1); E1 is 3 times more important than *lead free level* (E3); and E2 is 9 times more important than E3. By applying the reciprocal for inverse comparison defined in Table 6.2, we can deduce that E1 is 1/4 as important as E2, E3 is 1/3 as important as E1 and E3 is 1/9 as important as E2. Also, it is trivial that E1 has same importance as E2. This applies to E2 and E3. Using the above assumptions Section 1 of Table 6.6 is completed.

The second step is to sum the different values of the attributed weights. This is done as follows:

For the first column we have 1+4+1/3=5.33; second column is 1/4+1+1/9=1.36 and the third column is 3+9+1=13

The third step is to normalise the different attributed weights. This is obtained by dividing the individual attributed weights by the total obtained in the previous step above. For example, to normalise the entry E2-E1, the attributed weight value 4 is divided by the total sum of the attributed values for that particular column. Therefore, the normalised value is 4/5.33=0.75. Similiarly other values are obtained and presented in section 2 of Table 6.6.

The fourth step is to determine the average of all the normalised indicators along each row. For instance in section 2 of Table 6.6, the average for the first row is computed as (0.19+0.18+0.23)/3=0.2. Similarly, the average weights for the other two rows are computed.

The above steps are pursued for other criteria and the results are presented in Tables 6.7-6.11.

Table 6.6. Evaluation matrix of estimated weights of environmental indicators

		E1	E2	E3	Weights
Section 1	E1	1	1/4	3	
	E2	4	1	9	
	E3	1/3	1/9	1	
	Σ	5.33	1.36	13	
Section 2	E1	0.19	0.18	0.23	0.2
	E2	0.75	0.74	0.70	0.73
	E3	0.05	0.08	0.11	0.08

Table 6.7. Evaluation matrix of estimated weights of social indicators

	S1	Weights
S1	1	
Σ	1	
S1	1	1

Table 6.8. Evaluation matrix of estimated weights of economic indicators

	F1	F2	F3	F4	Weights
F1	1	1/2	5	6	
F2	2	1	4	7	
F3	1/5	1/4	1	3	
F4	1/6	1/7	1/3	1	
Σ	3.34	1.89	10.33	17	
F1	0.30	0.26	0.48	0.35	0.35
F2	0.60	0.53	0.39	0.41	0.48
F3	0.06	0.13	0.10	0.18	0.11
F4	0.05	0.08	0.03	0.06	0.06

Table 6.9. Evaluation matrix of estimated weights of technical indicators

	T1	Weights
T1	1	
Σ	1	
T1	1	1

Table 6.10. Evaluation matrix of estimated weights of physical indicators

	P1	P2	Weights
P1	1	1/5	
P2	5	1	
Σ	6	1.2	
P1	0.17	0.17	0.17
P2	0.83	0.83	0.83

Similarly, the evaluation matrix of the weights of the main sustainability indices is presented in Table 6.11.

Table 6.11. Evaluation of estimated weights of sustainability sub-indices

	$I_{S,1}$	$I_{S,2}$	$I_{S,3}$	$I_{S,T}$	$I_{S,P}$	Weights
$I_{S,1}$	1	3	2	5	4	
$I_{S,2}$	1/3	1	1/3	4	4	
$I_{S,3}$	1/2	3	1	5	5	
$I_{S,T}$	1/5	1/4	1/5	1	2	
$I_{S,P}$	1/4	1/4	1/5	1/2	1	
Σ	2.28	7.5	3.73	15.5	16	
$I_{S,1}$	0.44	0.4	0.54	0.32	0.25	0.39
$I_{S,2}$	0.15	0.13	0.09	0.26	0.25	0.18
$I_{S,3}$	0.22	0.4	0.27	0.32	0.31	0.3
$I_{S,T}$	0.09	0.03	0.05	0.06	0.13	0.07
$I_{S,P}$	0.11	0.03	0.05	0.03	0.06	0.06

Having determined the weights of the different indicators, the next step is to determine the different sustainability indices. Equations 6.1 and 6.2 are employed. These equations are applied on the different indicator values in Table 6.4. To provide clarity two examples are presented. The first deals with criteria of type "more is better" and the second deals with criteria of type "less is better".

To normalise the annual CO_2 saving for the module M2, the mathematical model in equation 6.1 is used. The variables of equation 6.1 are determined from Table 6.4 and their values are $I^+_{A,ij}$=1100, $I^+_{\max,j}$=1300, $I^+_{\min,j}$=800. Therefore, the normalised indicator yields: $I^+_{N,ij}$ = (1100-800)/ (1300-800) =0.6

To normalise the capital cost for the module M2, the mathematical model in equation 6.2 is used. The variables of equation 6.2 are determined from Table 6.4 and their values are $I^-_{A,ij}$=8000, $I^-_{\max,j}$=9000, $I^+_{\min,j}$=5000. Therefore, the normalised indicator $I^-_{N,ij}$ =1-[(8000-5000)/ (9000-5000)] =0.25.

Table 6.12. Normalised indicators

			Company1	Company 2		Company 3			Company 4	
		Weights	M1	M2	M3	M4	M5	M6	M7	M8
Environmental indicators										
Annual CO_2 saving	E1	0.2	1	0.6	0.4	0.98	0.4	0	0.3	0.2
Peak power or nominal output	E2	0.73	1	0.04	0	1	0.88	0.16	0.56	0.44
Lead free level	E3	0.08	0	0	0	0	0	0	1	1
Social indicators										
Supplier's experience	S1	1	0	0.47	0.47	1	1	1	0.61	0.61
Economic indicators										
Capital cost	F1	0.35	0	0.25	0.63	0.05	0.4	1	0.63	0.6
Annual cost saving	F2	0.48	1	0.6	0.2	0.82	0.2	0	0.26	0.16
Energy pay-back time	F3	0.11	0	0	0	0	1	0.83	1	1
Warranty	F4	0.06	1	1	1	0	0	0	1	1
Technical indicators										
Conversion efficiency	T1	1	1	0.62	0.48	0.91	0.76	0	0.75	0.54
Physical indicators										
Weight	P1	0.17	0.25	0.79	1	0.14	0.14	0	0.34	0.31
Module area	P2	0.83	0.06	1	1	0	0	0.31	0.36	0.36

Based on Table 6.11, the individual sustainability index for environmental, social, economic, technical and physical groups are calculated using average weights in the first column of Table 6.12. For example, the environmental index *($I_{S,1}$)* for the module M2 is computed as: 0.2*0.6+0.73*0.04+0.08*0=0.15. Similarly, the sustainability indices for the social, economic, technical and physical parameters are computed and presented in Table 6.13. After obtaining the different sustainability indices, it is important to aggregate the indices to determine the level of sustainability of each PV-module. This is computed using the different weights of the sustainability indices deterimined in Table 6.11. As an example, the sustainability index for the module M2 is calculated as follows S_I=0.39*0.15+0.18*0.47+0.3*0.47+0.07*0.62+0.06*0.96=0.39. Similarly, the S_I for other modules are calculated and included in Table 6.13.

Table 6.13. The total sustainability indicator

	Weights	M1	M2	M3	M4	M5	M6	M7	M8
$I_{S,1}$	0.39	0.93	0.15	0.08	0.93	0.72	0.12	0.55	0.44
$I_{S,2}$	0.18	0	0.47	0.47	1	1	1	0.61	0.61
$I_{S,3}$	0.3	0.54	0.47	0.38	0.41	0.35	0.44	0.52	0.46
$I_{S,T}$	0.07	1	0.62	0.48	0.91	0.76	0	0.75	0.54
$I_{S,P}$	0.06	0.09	0.96	1	0.02	0.02	0.26	0.36	0.35
S_I		0.60	0.39	0.32	0.73	0.62	0.37	0.55	0.49

For ease of interpretation, Table 6.13 is graphically represented in Figure 6.12, where an examination on the selection of different PV-modules and suppliers using single and multi-criteria analysis techniques will be conducted. This will provide a basis for modelling semantic web selection queries for selecting different PV-systems and/or components.

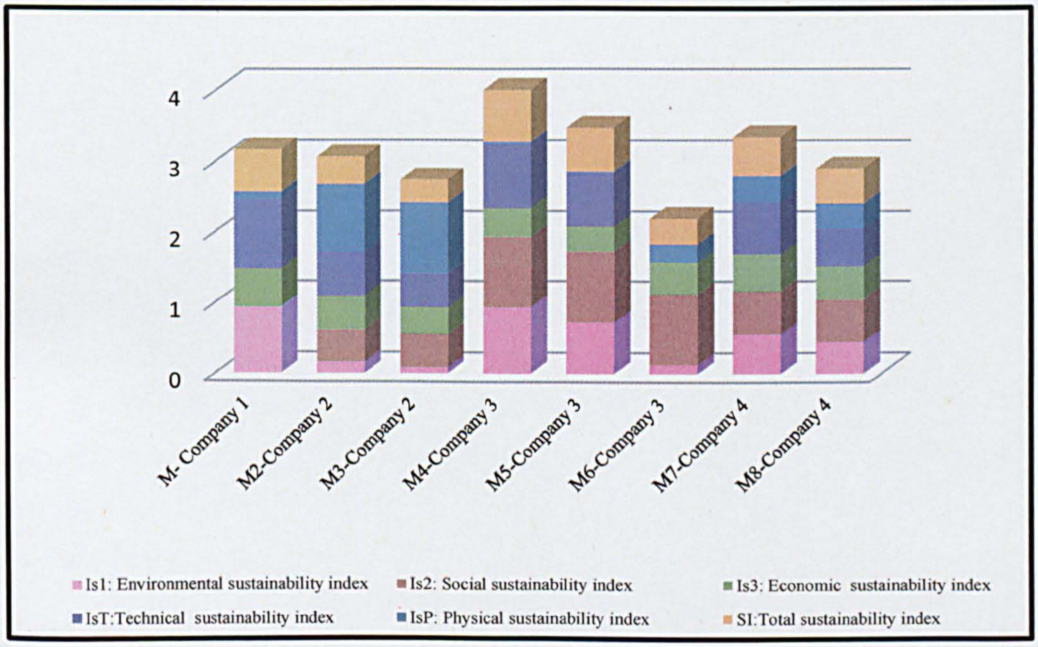

Figure 6.12. Selection of PV-module using multi-criteria decision analysis

From Table 6.13, a decision can be made based on the PV-module with the best sustainability index. For instance, the module with the highest sustainability index is M4 with sustainability index 0.73. M4 has the lowest physical index of value 0.02 which is an advantage in the sense that it will not weigh and occupy too much space on the roof. It has also the highest technical and environmental index with a value of 0.91 and 0.93 respectively. However, it is not so obvious to make a decision on the economic index of M4 which is 0.41. This is because it contains both negative and positive indicators from a client's perspective. For instance, high capital cost and long energy payback period are negative indicators and discouraging to clients. Comparing the economic index of M4 to M7, it can be concluded that M7 has a higher economic index than M4. However, on comparing the capital costs and annual cost savings, M4 has both high capital cost and annual cost savings of £8 800 and £355 respectively compared to £6 500 and £215 of M7. This is the main weakness of multi-criteria decision analysis techniques. Once the final index (Table 6.13) has been calculated, it is not always possible to make decisions based on Table 6.12 without necessarily revisiting its base table (Table 6.4). This weakness is overcome in PV-TONS.

From the above, the PV-system concepts including instances, data-type properties, data-type values, object-type properties and classes have been completely specified. This is in accordance with the CommonKADS methodology. However, according to recent development in ontology development, OWL properties such as transitive relations, symmetric, functional properties and OWL property restrictions can greatly enrich ontological knowledge models. However, these properties cannot be defined in CommonKADS. These additional properties are best modelled in a software environment; hence will be considered in Chapter 7. Nontheless, as earlier argued a full OWL knowledge model is still very limited in semantics and thus limited reasoning in practical situations. Thus, the extension of OWL to include a SWRL is often recommended. In this section the elicitation of rules to be implemented in PV-system OWL ontology will be examined.

6.9 Formulation of rules in PV-system ontology

In this study four techniques have been used in deriving rules for implementation in PV-system OWL ontology. The first two techniques are based on the UML concept and composition properties reviewed in Chapter 3. The last two techniques are based on the laddering techniques of knowledge elicitation reviewed in Schreiber *et al.* (2000). The two techniques are the decision and process ladders. In the ensuing sections, these techniques will be examined and examples of how rules have been formulated to be used in PV-system OWL ontology will be illustrated.

6.9.1 Formulation of rules based on UML concept hierarchical relationships

The classes in the concept are related through the *is-a* relationship. An example is "a grid-connected system *is-a* type of PV-system". Based on the UML model of Figure 6.9, rules can be formulated on the parts of the model which respect to a concept hierarchy. An example is the establishment of the different types of PV-systems that can be constituted from a given pool of existing PV-system components. A rule can be formulated as:

If (PV-system components are known)

Then (the different PV-systems should be determined)

6.9.2 Rule formulation based on UML composition relationships

As reviewed in Chapter 3, a composition relation shows the way a knowledge object is composed of its constituent parts. An example of composition relationship is "a module panel is composed of modules". Based on Figure 6.9, rules can be formulated on the parts of the model with respect to a concept hierarchy. An example is the investigation of the different components of a PV-system. A rule can be formulated to aid this investigation as:

If (a type of PV-system is known)

Then (its constituent components should be determined)

6.9.3 Formulation of rules based on decision ladder relationships

A decision ladder shows the alternative course of action for a particular decision. It also shows the pros and cons for each course of action. An example of a decision ladder is shown in Figure 6.13. It is important to note that the decision ladder in Figure 6.13 has been drawn using the data-type properties extracted from the UML model of Figure 6.9.

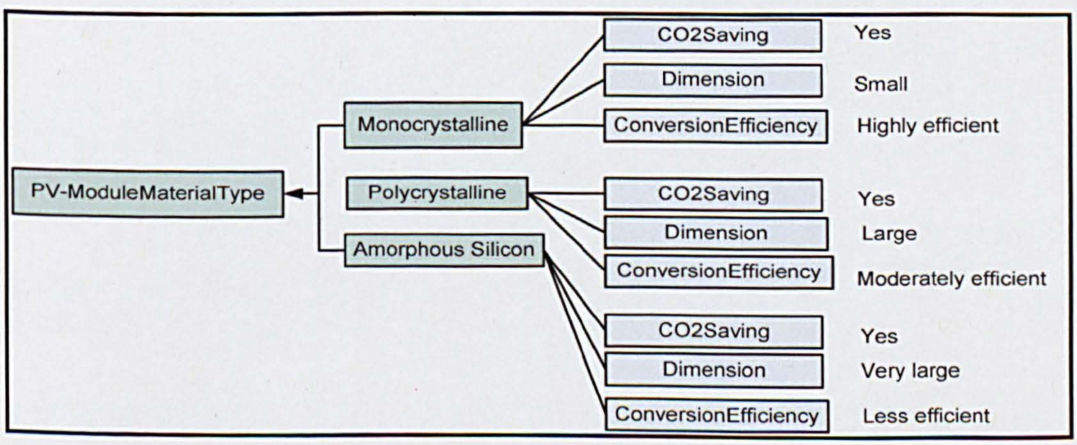

Figure 6.13. PV-module decision laddering

Based on Figure 6.13 decision rules were formulated and used in reasoning. The following two examples illustrate how rules have been formulated. The first rule is about how to list all the less efficient PV-modules. This is formulated as:

If (a PV-module has material type (*PV-ModuleMaterialType*) amorphous silicon)
Then (the PV-module conversion efficiency (*ConversionEfficient*) is *Less efficient*)

Although the above rule uses the module material type as a condition of selection, it is also possible to use other constraints such as numbers to specify constraint limits. In the second example, a rule that uses a property value as a condition for selection is presented.

If (a PV-module has conversion efficiency greater than 0.8)
Then (classify the PV-module as highly efficient)

6.9.4 Rule formulation based on process ladder relationships

A process ladder is used in showing tasks and sub-tasks in a process. An example of a process ladder is presented in Figure 6.14.

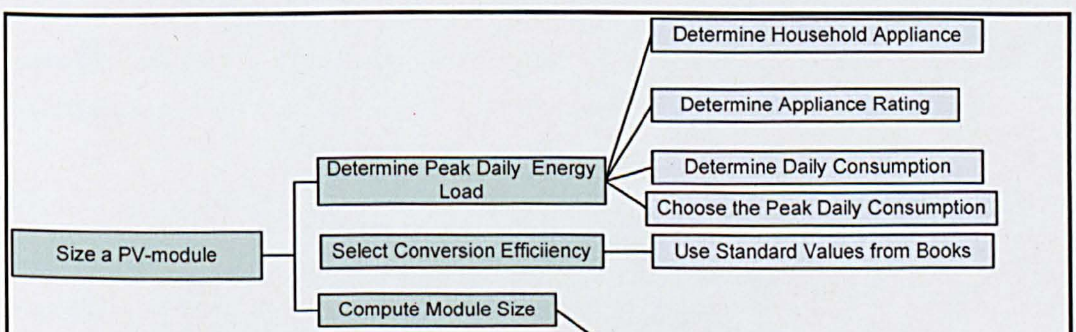

Figure 6.14. Process ladder for the sizing of a PV-module

A rule formulated based on the process ladder for sizing a PV-module given the peak daily energy consumption and the efficiency of the PV-module is as follows:

If (the peak daily energy consumption of a building and the efficiency of a PV-module are known)
Then (calculate the PV-module size)

In sections 6.9.1 to 6.9.4, examples of rules formulated have been presented. Taking into consideration the structure of the PV-system UML knowledge model and its associated properties, a huge number of rules can be formulated. The number of rules will further increase and the formulation task will become complex when OWL restrictions, inverse, transtive and functional properties are considered. Therefore, the rules developed in this study will be presented in the implementation chapter.

6.10 Conclusion

In this chapter, the CommonKADS knowledge engineering methodology was pursued in developing conceptual models about the domain of sustainable building technology. The conceptual models have been developed using the UML knowledge modelling language. Given the intended PV-system application to be developed in this study, the process model which depicts the information and steps that facilitate the selection and acquisition of PV-systems was developed. This process model facilitated the abstraction of process concepts which could not have been straightforwardly captured. Some examples are the "rough sizing of PV-modules" and the "sizing and selection of other components".

Also, in the acquisition and transformation of lightweight taxonomies into conceptual knowledge models from literature sources, the PROMPT methodology was used in the semantic verification of concepts. The key attributes that can be used in the selection of different PV-modules were established in this chapter. To facilitate understanding, the attributes were classified into the economic, environmental, social, technical and physical categories. These were used in computing a composite sustainability index. This index and the attributes are used as indicators in measuring how sustainable (with respect to the five attributes categories) a PV-array is. To illustrate how to compute the sustainability index, eight different PV-modules belonging to four different suppliers were selected from the Green Book Live website and their data values were abstracted and used. This led to the establishment of graph-based multi-criteria system that can facilitate visual decision-making on the different types of PV-modules. After examining how decision rules can be formulated for inferencing knowledge about the different PV-systems and/or components, it is necessary to examine how these and even more decision rules could be implemented in a semantic web environment or using a semantic web language. This requires that the UML models, including object, data properties of sustainable building technologies be input in a software environment. The challenge is how to implement the conceptual models in a software environment? For the purposes of this study, the UML conceptual models will be converted to OWL knowledge models using ArgoUML, an automatic tool for converting UML to OWL. However, because of loss of data that emerges from the process of automatic conversion from UML to OWL, the OWL ontology will be manually refined to form the required ontology knowledge model. This will constitute the core of this study as the resultant ontology will be implemented in various software environments that will be integrated to form the sustainable building technology semantic web environment. As highlighted in section 6.4.3.1, ontological components that have not been able to be captured by the CommonKADS methodology will now be modelled in the chosen ontology editor. This is because these ontological components are best handled through implementation in a software environment. The components include annotation properties, property restrictions and knowledge model instances. However, modelling these components in an ontology editor present two major challenges. The first challenge is defining restrictions in the ontology. For instance, what will be the different number of values to be attributed to PV-module material types? Will the material types be limited to just the three commonly available types (polycrystalline, monocrystalline and thin-film amorphous silicon) in the UK markets? How will the CO_2 content of a module be specified? Will the specification be numeric or Boolean? Will it be more appropriate to simply model CO_2 as Boolean so that the accepted values for the module CO_2 content can be "yes" or "no"? Will attributing numeric values such as $KgCO_2$ per m^2 of PV-module more appropriate than the Boolean values? The second challenge concerns the abstraction of instances from different literature sources? Will the instances be manually or automatically extracted? The former is easy for very small data set? The latter is faster for very large data sets but unfortunately, the formats in which companies publish their information cannot easily be exploited using automatic tools. These challenges will be addressed in Chapter 7.

7. DESIGN AND IMPLEMENTATION OF PROTOTYPE SYSTEM

7.1 General

An overall knowledge model of the sustainable building technology model has been developed and presented in UML format in Chapter 6. The classes, object and data properties of the PV-system were spelt out. For purposes of this study, rules that can facilitate reasoning in the PV-system ontology component were presented. The challenge remains in the implementation of these knowledge concepts in a software environment.

This chapter discusses the system requirements in which the tasks to be performed by the ontology knowledge-based system have been clearly specified. The chapter introduces the system architecture for developing semantic web applications and further exploits the semantic web tools reviewed in Chapter 3 in configuring this architecture. Based on the system architecture the sustainable building technology knowledge model is implemented on its two main components. Firstly, the knowledge model is implemented in an ontology editor where editing of the knowledge model is conducted. Secondly, the knowledge model is implemented in a rule-based editor where SWRL rules are edited to facilitate reasoning over the PV-system. Key in this chapter is how to fit the knowledge models developed in the previous chapter into the different components of the proposed system architecture. A transformation procedure of the UML knowledge models to OWL has been presented. This chapter also elaborates on how in the course of the transformation of UML knowledge model to OWL, the knowledge model was enriched with OWL language constructs lacking in UML. Furthermore, an illustrative example of how a rule is implemented in the main development tool, Protégé-OWL was presented. Based on the huge size of the OWL knowledge model file, some screenshots of key aspects including top ontology concepts, an excerpt of the OWL ontology and some sample rules and queries have been presented. The complete knowledge-based system known as PV-TONS in OWL file format is in appendix 7.1.

7.2 System requirements

The establishment of system requirements is imperative in the development of knowledge-based systems as this specifies the tasks to be performed by the knowledge base. The task to be performed by the knowledge base depends on the knowledge requirements specified by the CommonKADS methodology. In Chapters 5 and 6 it was highlighted that the knowledge requirements should provide information that can be used in the design and selection of PV-system components. This implies that the system or PV-TONS requirements should provide the means by which PV-systems can be designed and their respective components selected. The purpose of this section is to discuss the various strategies used to build a semantic web system for the management of sustainable building technology and PV-system information. This chapter identifies the requirements to be fulfilled by the sustainable building technology ontology and PV-TONS. They are summarized as follows:

- Provision of a central knowledge base where sustainable building technology and PV-system information can be stored and/or retrieved;

- The system should be an open source. The PV-TONS ontology, a core output of this research should be in a language and domain that anyone can exploit and process the information with appropriate tools of their choice. It is hoped that after publishing the ontology in a reputable journal it will be loaded onto the freely available Protégé-OWL ontology library hosted by the Stanford Center for Biomedical Informatics Research at the Stanford University School of Medicine ;

- The system should be agile in nature: To achieve this we have chosen an ontological model that allows to dynamically reorganize relationships between classes, properties and objects without constraints of usual tools for data or object modelling (UML, relational databases, etc);

- The system should support reasoning. This entails the creation of some constraints and rules that may contextualize the information related to the role of class and properties for reasoning;

- Provision of the possibility of the PV-TONS to adapt and evolve with minimal disruption. New ontologies can be defined and added incrementally without the need for the redesign of the environment.

Given these requirements, it was decided that the implementation would be platform independent. The platform will allow transparent access to distributed entities over a heterogeneous network of machines and operating systems. At the functional level, the platform independence of the system was achieved by using Protégé-OWL which is written in Java. Java is a programming language capable of moving without constraints from one computer to another. Section 7.3 examines the different software components that have been used to achieve the above requirements.

7.3 Software components identification

Having justified the importance of the different semantic technologies in Chapter 3, this section summarises those used in developing the PV-TONS.

- Protégé-OWL 3.4.4: This is the ontology development editor developed in Stanford University. It is an open-source tool that enhances end-users skills in creating, visualizing, and updating ontologies. It is very extensible and can accommodate other plug-ins with the use of its Java API (see chapter 3 for more on Protégé-OWL 3.4.4);

- SWRLTab: This is a Protégé-OWL plug-in and editor that facilitates the writing of SWRL rules;

- JessTab: This is a Protégé-OWL plug-in that allows the use of Jess and Protégé-OWL together;

- Jambalaya: This is a Protégé-OWL plug-in that enables the visualisation of the ontology class hierarchies;

- SQWRL: This is a SWRL-based language for querying OWL ontologies (O'Connor and Das, 2009). It provides SQL-like operations to retrieve knowledge from OWL;

- Pellet 1.5.2: Pellet is an OWL 2 reasoner which provides standard and cutting-edge reasoning services for OWL ontologies. Although pellet currently exists in different versions; pellet 1.5.2 is the version that has been incorporated in Protégé-OWL 3.4.4, the ontology editor chosen for this study.

7.4 System architecture

In Chapter 3 a generic architecture for developing a semantic web application was examined. In presenting the architecture, an N-tier approach was chosen to highlight the fact that a potential real life semantic web application should have a web browser for accessing information from the database tier. However, within the scope of this study, the N-tier architecture of Figure 3.5 was reduced to two main layers for development of the sustainable building technology ontology and PV-TONS. The two main layers are the application logic and the database tier as presented in Figure 7.1. In each layer, one or more technological components are involved.

7.5 System implementation

The implementation will be performed according to each technology involved in a given layer. In order to demonstrate how one layer feeds the other, the database server implementation will be conducted before the application layer.

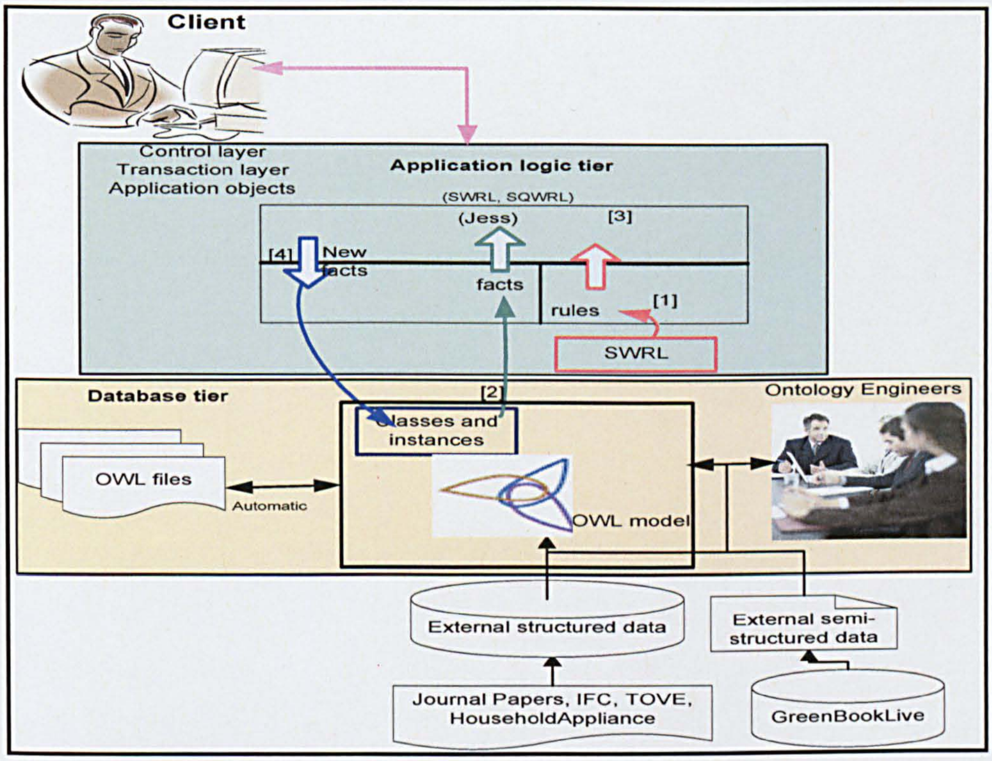

Figure 7.1. Sustainable building technology ontology and PV-TONS architecture

7.5.1 Implementation in the database tier

In this layer four main technologies have been considered. The main technology in this layer is the Protégé-OWL knowledge representation model which can store information about any domain of discourse. The Protégé-OWL knowledge model can be converted into different file formats such as OWL file, RDF, XML for other uses such as in application development. In this study, the OWL file was chosen as one of the storage format. For persistence storage, the Protégé-OWL knowledge including SWRL rules is often stored in a database management system, MySQL, PostgreSQL and Protégé server. The use of database servers is important especially in case where the ontology is very large and involved multiple developers. Having split the domain of discourse of the ontology into two, i.e. a domain ontology based on generic sustainable building technology and an application ontology based on the PV-system, the size of the ontology is easily managed as a file stored on the local computer. Moreover only one developer is involved in the ontology development process and hence does not warrant a separate database server to store the ontology that would have been required by a significant number of developers. As such a database management system was not required.

The main challenge in this layer is how to transform the PV-system UML object-oriented knowledge model of Figure 6.9 into the Protégé-OWL knowledge model. This challenge was overcome by using two main techniques. Firstly, an UML-OWL coversion tool, ArgoUML was used to transform the UML object-oriented knowledge model to OWL. This resulted in some loss of data. Secondly, a manual process was used to improve on the OWL knowledge model that emerged from the use of ArgoUML. Some transformation rules were used to completely enrich the OWL model obtained from ArgoUML. Of recent, the transformation from a UML model to an OWL model has received considerable interest (Berardi *et al.* 2005; Dong *et al.* 2007; Brockmans *et al.* 2004; Gaševič *et al.* 2004). The details of these studies are out of the scope of this study. However, one important consequence of these studies is the establishment of rules that map UML to OWL. Some of the main rules were used (see Table 7.1) in the transformation of some key components of the PV-system ontology UML model to PV-system-OWL model. It is important to note that these rules were used to improve on the OWL output generated from the transformation of UML to OWL through the use of the ArgoUML software discussed in the methodology chapter.

Table 7.1. Transformation rule of UML into OWL

UML	OWL
Class	Class
Attribute	Data-type property
Association	Object property
Generalisation between classes	subClassOf
Generalisation between association	subPropertyOf
Multiplicities	Cardinalities
Multiplicity constraint	Functional property

Based on Table 7.1, the implementation in the three main technologies considered in the database layer will be pursued. These are the implementation in the Protégé-OWL environment, the ontology storage environment and the implementation in the rule-based environment.

7.5.1.1 Implementation in an ontology modelling environment

The best and most organised method is by adopting the methodology proposed by Noy and McGuinness (2001) summarised and presented in Figure 7.2.

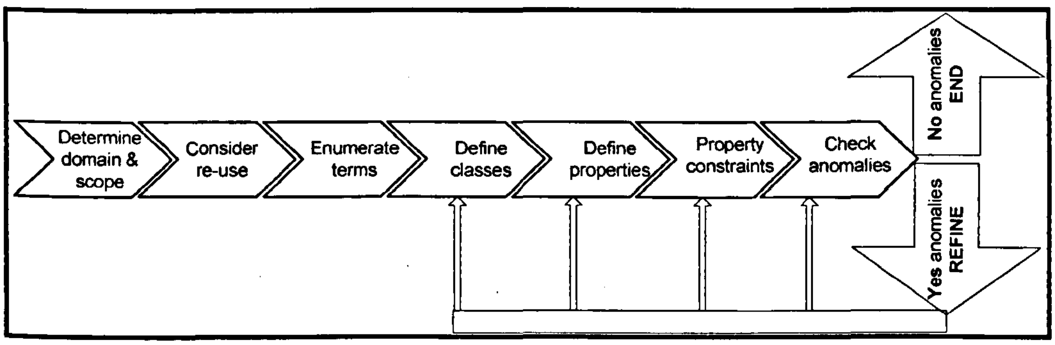

Figure 7.2. Ontology development process

The CommonKADS methodology discussed in Chapter 6 led to the complete achievement of the first five steps of Figure 7.2 which are the determination of the domain and scope, consideration of existing ontologies for possible re-use, enumeration of terms, and definition of classes. Although the CommonKADS was used to establish the object and data-type properties, the characteristics of these properties were not defined. For instance, CommonKADS does not provide a means of specifying a property as being functional or transitive. Hence, this section will focus on the last four steps of the ontology development process of Figure 7.2. Furthermore, CommonKADS does not offer the possibility of defining restrictions as highlighted in section 6.7.

Properties of classes

The three types of properties often considered are the object, data and annotation properties. In ontology modelling, properties are very important as they describe the relations between concepts and consequently between instances of the concepts. The practice in modelling properties in ontology engineering is to define the property in such a way that it can easily fit into a complete sentence, especially linking an object to a subject. For instance, one of the properties linking PV-system to supplier is "supplier". This can be modelled as PV-system *hasSupplie*r supplier A, per se. This tradition is adopted in this study.

Commencing with the sustainable building technology, the transformation of its object properties is presented in Figure 7.3.

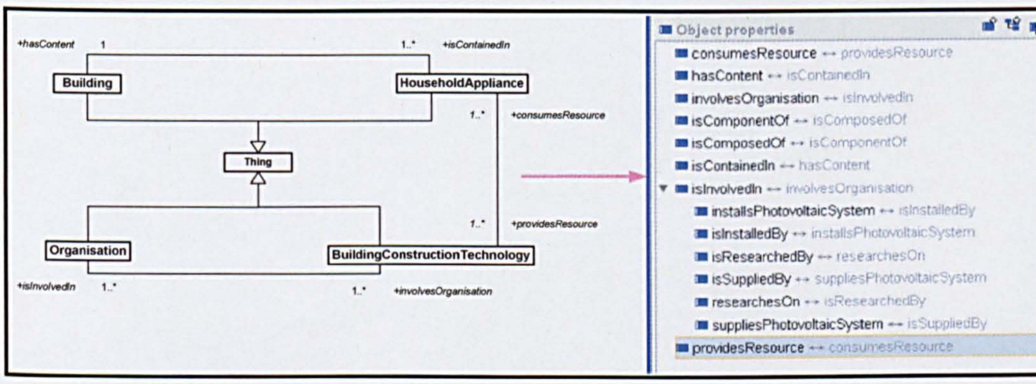

Figure 7.3. Conversion of UML relations to object properties of sustainable building technology ontology

The transformation of the data-type properties is done for each concept of the sustainable building UML knowledge model. As an example, the transformation of the UML attributes to OWL data-type properties of the *BuildingConstructionTechnology* concept is presented in Figure 7.4. In a similar manner the UML attributes of the Building, HouseholdAppliance and Organisation concepts are transformed to OWL data-type properties and implemented in Protégé-OWL 3.4.4.

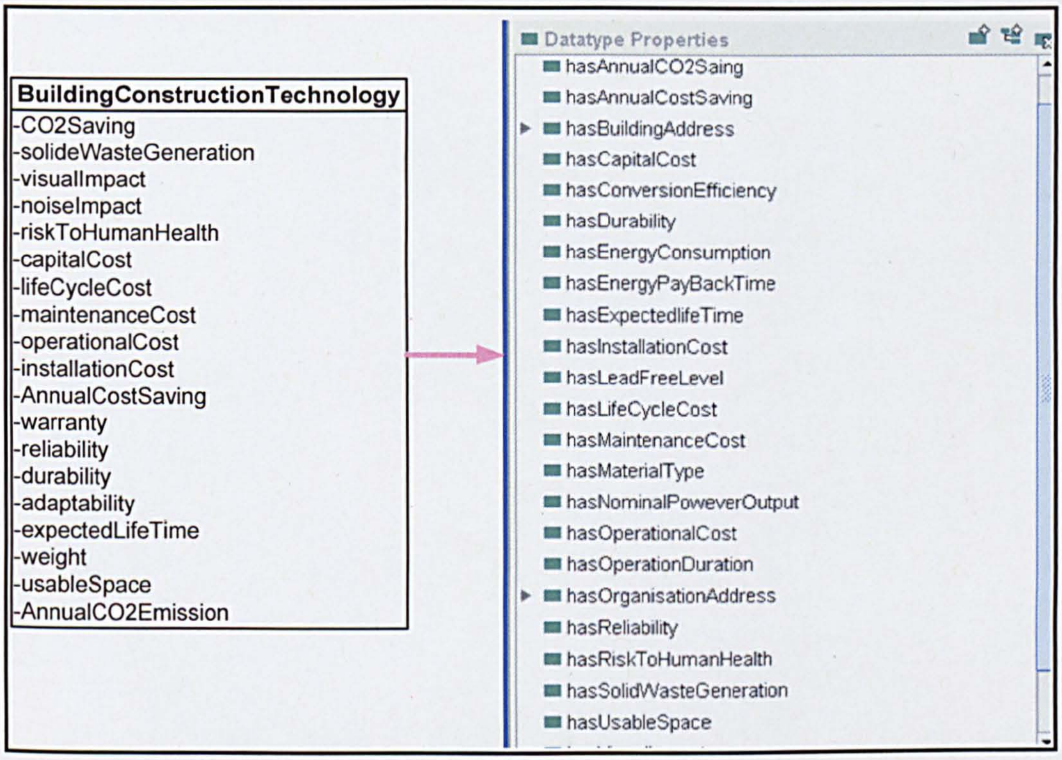

Figure 7.4. Conversion of UML attributes to data-type properties of sustainable building technology ontology

Given that the annotation property is used to clarify or provide more information about objects, it is best tagged against the objects and therefore best implemented in a software environment. In Figure 7.5, the defintion of the sustainable building ontology is highlighted identified as an "rdf: comment". This refers to an annotation property. Hence, using the object properties and data-type properties of Figures 7.3 and 7.4, the domain knowledge model of the sustainable building technology ontology is presented in Figure 7.5. The annotation property of each object will only be visible when the object is clicked.

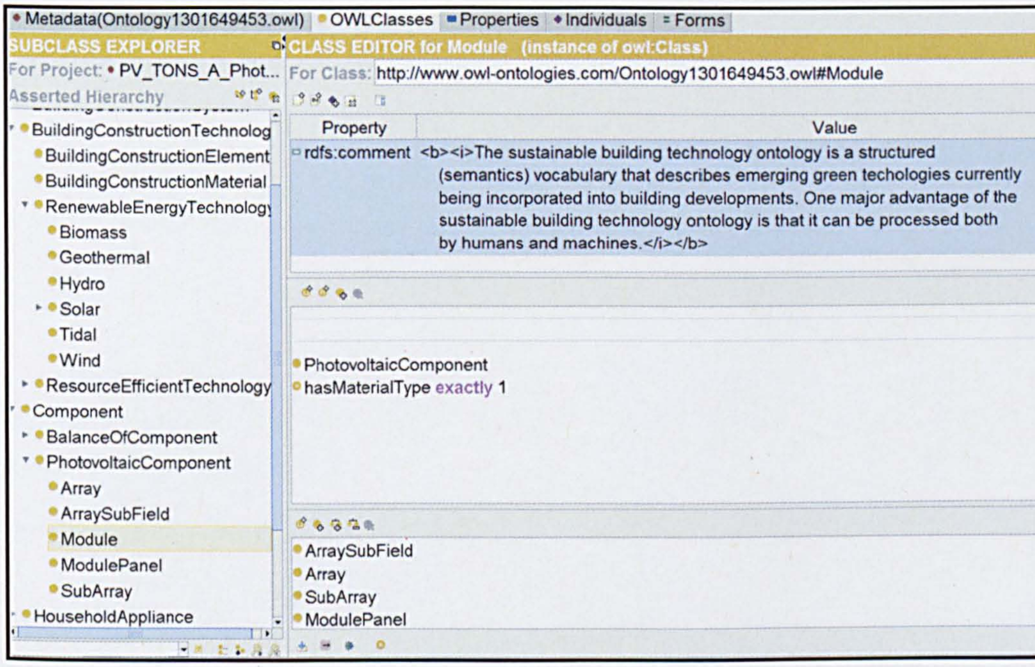

Figure 7.5. Sustainable building technology ontology in Protégé-OWL 3.4.4

With respect to the PV-system ontology, its object properties are *hasComponent, hasSupplier, installsProduct,* and *researchesOn.* The *hasComponent* property relates the set of individuals belonging to the domain of PV-system to the set of individuals belonging to the domain of PV-system component. The property *hasSupplier* defines the organisations supplying PV-system in the UK. The property *installsProduct* defines the companies involved in the installation of PV-systems in the UK. The property *researchesOn* defines the institutions in the UK that research on the domain of PV-system. The conversion of the PV-system object properties is depicted in Figure 7.6.

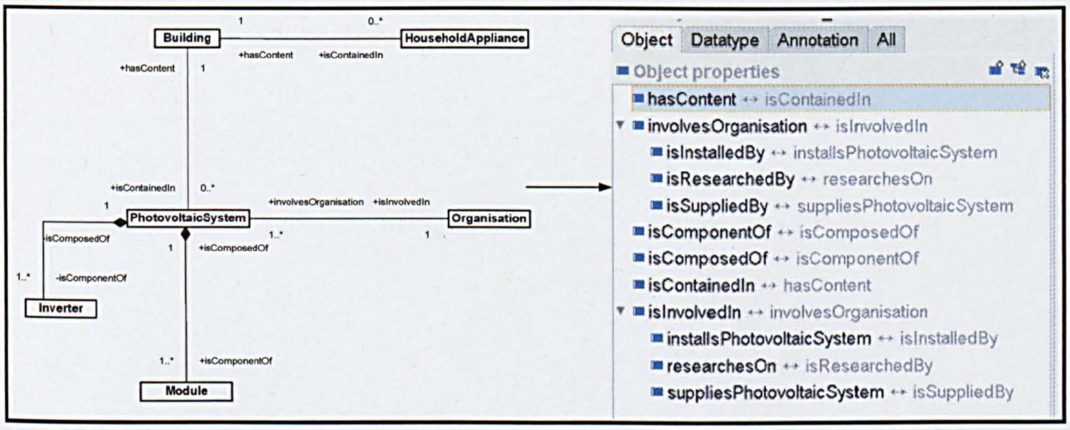

Figure 7.6. Conversion of UML relations to object properties of PV-system ontology in Protégé-OWL

The main data properties of the PV-system ontology are *hasAddress, hasArea, hasModuleEfficiency,* and *hasModuleWeight.* The *hasAddress* property defines the address of various organisations with interest in PV-system. The *hasArea, hasModuleEfficiency,* and *hasModuleWeight* properties define the dimensions, efficiencies and weight of various PV-modules available in the UK market.

For clarity of the PV-system ontology, the annotation type properties have been used in adding various pieces of information/meta-data to some components of the PV-system ontology in the Protégé-OWL editor.

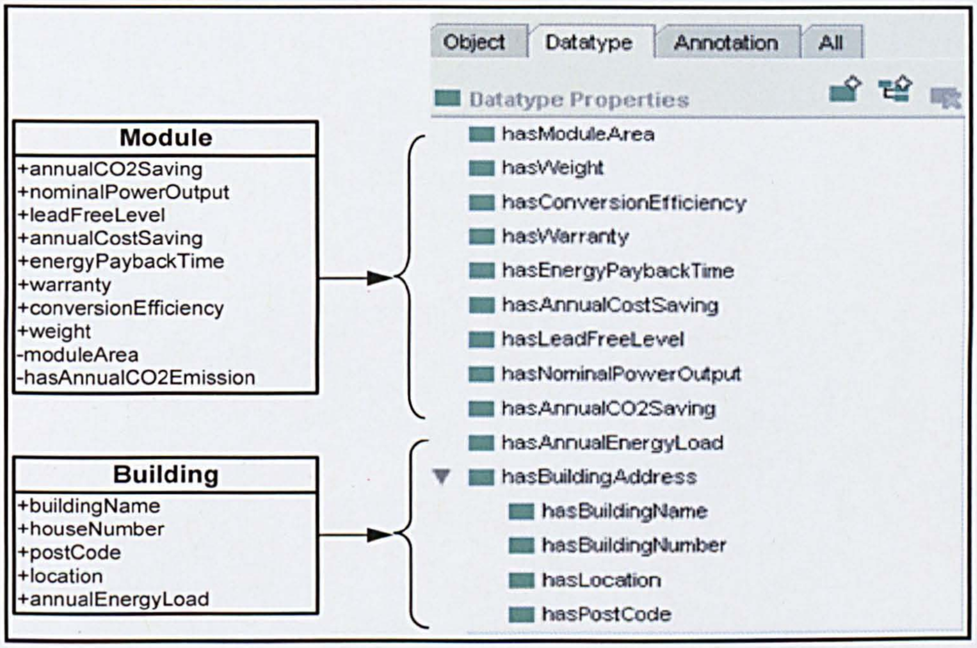

Figure 7.7. Conversion of UML attributes to data-type properties in protégé-OWL

In the literature properties can be functional, can have inverses, symmetric, and transitive. A property is *functional*, if for a given individual there can be at most one individual that is related to the individual via the property. The representation of a functional property is depicted in Figure. 7.8. The modelling of these properties are achieved by a simple "tick box" in the Protégé-OWL editor, consequently only the functional property will be shown in Figure 7.8 while the others will be described without being represented in a figure.

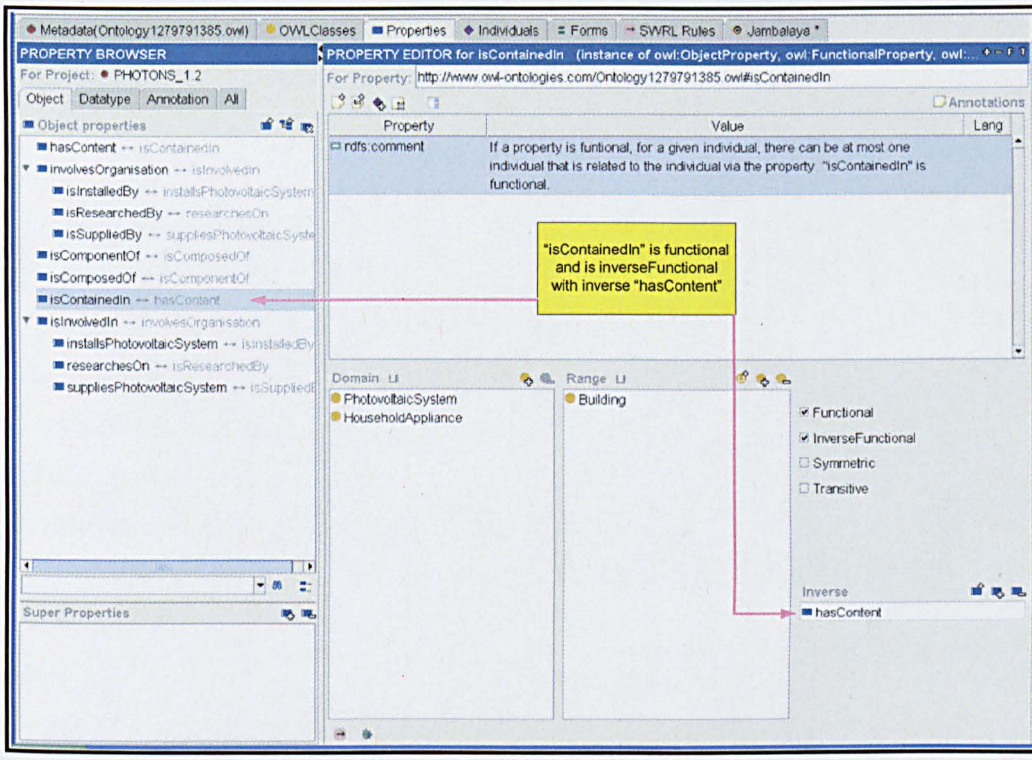

Figure 7.8. Functional properties in Protégé-OWL 3.4.4

The object property *isContainedIn* is functional with domains *PhotovoltaicSystem* and *HouseholdAppliance* and range *Building.* This means an instance of *HouseholdAppliance* can only belong to an instance of a *Building*. A refrigerator cannot belong to two different buildings. If refrigerator 1, an instance of *HouseholdAppliance* belongs to *building 1* and *building 2* instances of *Building*, then *building 1* and *building 2* must be the same instance. With respect to *PhotovoltaicSystem*, although an instance of a PV-system can be installed in such a way that it serves two buildings, for computation clarity it was decided that an instance of a *PhotovoltaicSystem* will be contained in an instance of a *Building*.

A property has an *inverse* if some property links individual A to individual B then its inverse property will link B to individual A. Generally, a property denotes a directional relationship of a given individual A to B. For instance, a supplier instance Solar Century supplies a PV-1, an instance of PV-system. Logically, *supplies* property by itself reveals no information about whether there is a corresponding relationship in the other direction.

An ontology engineer can create an opposite relationship from PV-1 to Solar Century, by designing the property as the inverse property of *supplies*, call it *isSuppliedBy*. The link from B to A can now be read as PV-1 *isSuppliedBy* Solar Century.

A property P is *symmetric*, if given any two individuals A and B, the property relates individual A to individual B then individual B is also related to individual A via property A. Unlike the inverse properties, a symmetric property is a relationship that is applied in both directions. In the sustainable building technology ontology, *GreenBuildingTechnology isSynonimous* to *SustainableBuildingTechnology*. The inverse example is Sustainable Building Technology *isComposedOf PhotovoltaicSystem* and *PhotovoltaicSystem isAType* of *SustainableBuildingTechnology*.

A property P is *transitive* if the property P relates individual A to individual B, and also individual B to individual C then it can be inferred that individual A is related to individual C via property P.

Like in the inverse property, transitive properties assert information about the relationship of the individuals related by these properties. A transitive property is commonly used to represent part-whole relationships.

Facets of properties

Facets are constraints on properties defined in the previous step. Facets limit the possible values for a property. There are three types of facets describing the property types. They are the value types, allowed-values and the number or cardinality.

Value type

This is the specification of the type of value assumed by a data-type property. For instance *hasAddress* has a string value.

Cardinality

Property cardinality defines how many values a property can have. The allowed classes for properties of type instance are often called a *range* while the classes to which a property is attached are called the *domain* of the property. An example of a property cardinality is presented in Figure 7.9.

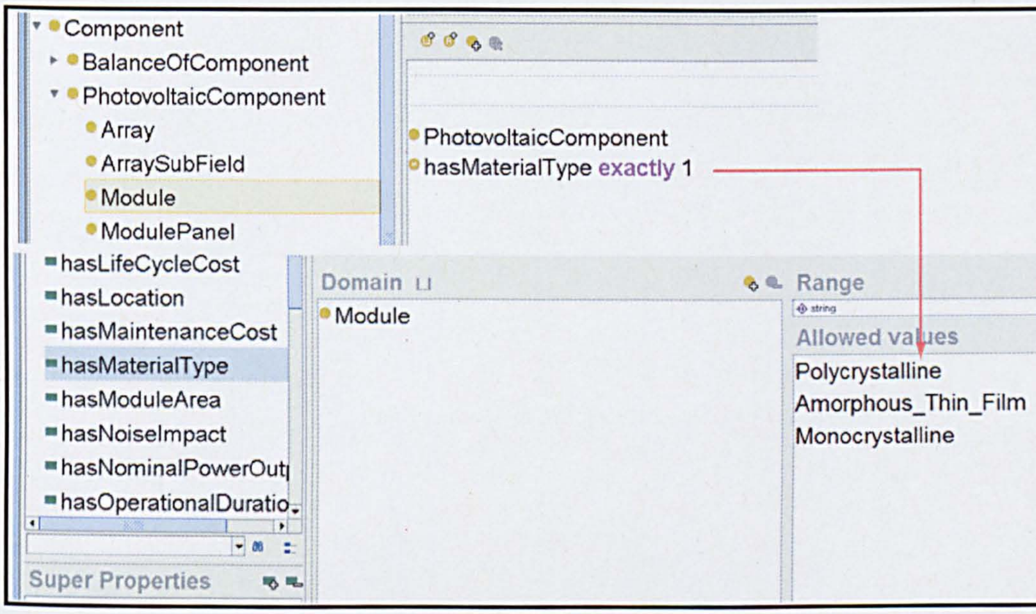

Figure 7.9. Cardinality property's restriction in Protégé-OWL

In Figure 7.9, the *hasMaterialType* is a data-type property. It denotes the type of material a PV-module is made up of. As reviewed in Chapter 2, it can either be a monocystalline, polycrystalline and amorphous-thin-film. These are the allowed values. Their types or range is a string. The constraint on this property is that a PV-module can have only 01 material. In order words, if a PV-material is made up of a monocrystalline material it cannot be made of polycrystalline material and vice versa.

Creation of instances

This step requires populating individual classes with instances. This activity consists of 1) choosing a class, 2) creating an individual instance of that class and 3) filling in the property values. The instances were manually abstracted from the Green Book Live database and manually edited into Protégé-OWL 3.4.4. This was because PV-system suppliers published most of their information using different formats that cannot easily be accessed using automatic tools. The extracted instances are edited in Protégé-OWL 3.4.4 as presented in Figure 7.10.

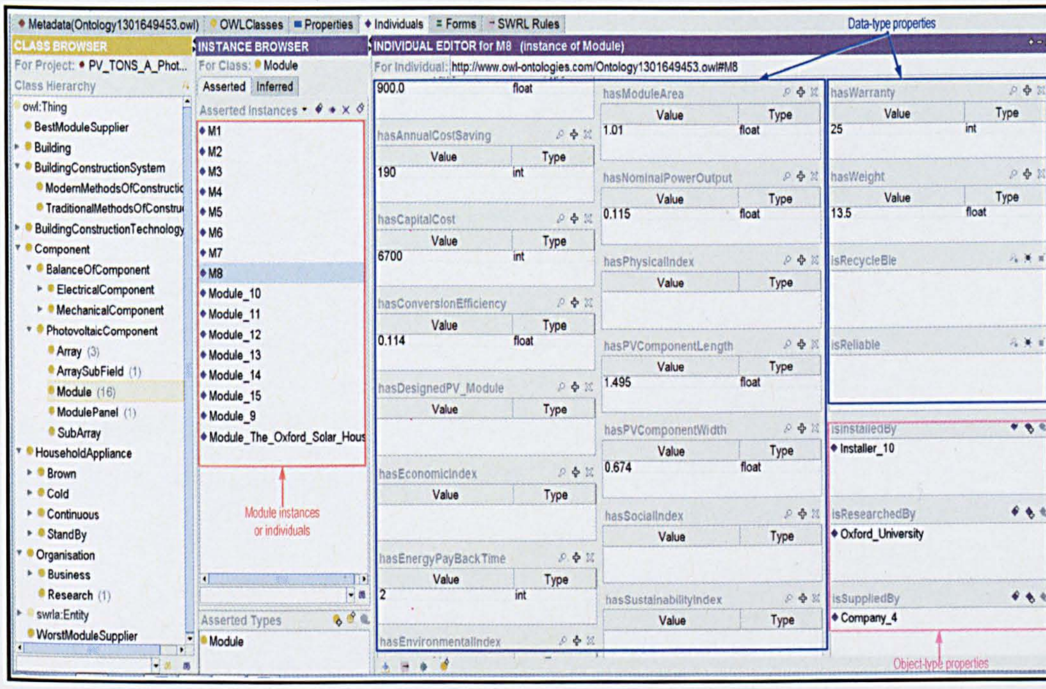

Figure 7.10. Instances and their properties in Protégé-OWL

Usually, it will suffice for a knowledge model to be called an ontology if it consists of classes, object properties, data-type properties and annotation properties. Most ontologies common in the literature generally consist of the afore-listed ontology concepts. However, knowledge elicited about PV-systems includes these concepts but goes beyond to include composition relations represented in Figure 6.8. The UML composition relations is one of the properties lost in the UML conversion process to OWL using ArgoUML. In Figure 7.11, the transformation of an excerpt of the UML composition relation of Figure 6.8 to OWL is presented.

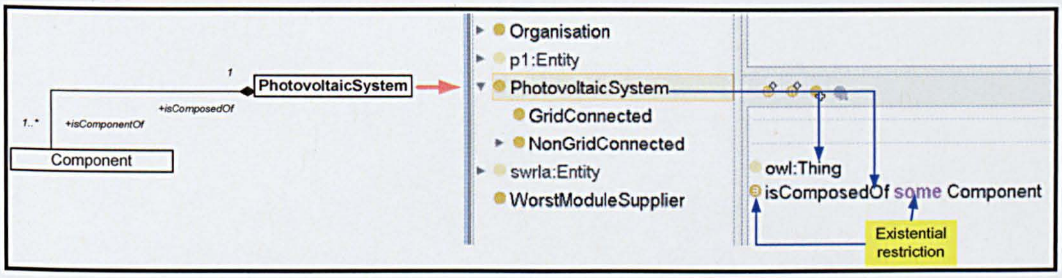

Figure 7.11. Conversion of UML composition relation to OWL

From the UML concept on the left of Figure 7.11, a *PhotovoltaicSystem isComposedOf Component*. The multiplicities from the *PhotovoltaicSystem* to *Component* are 1 and 1...* respectively. This is a one-many relationship common in object-oriented techniques. In order words if a *PhotovoltaicSystem* exists, it must have at least one *Component*. Generally, in ontology engineering the composition relationship can be modelled using the existential restriction on concepts. Existential restrictions also known as "someValuesFrom" or "some" restrictions denoted in DL syntax using $\exists$ - a backwards facing E. Existential restrictions describe the set of individuals that have *at least* one specific kind of relationship to individuals that are members of a specific class (Horridge *et al.*, 2007). In the right hand side of Figure 7.11, the *PhotovoltaicSystem* is a subclass of the generic concept Thing. If the *PhotovoltaicSystem* exist (denoted by $\exists$) then it must be composed (denoted by *isComposedOf*) of some (denoted by "some" representing existential restriction) components. This translates to the UML model on the left hand side of Figure 7.11.

After the establishment of ontological properties, restrictions and population of the knowledge model with instances, the product obtained is a complete PV-system ontology. This is presented in Figure 7.12. It is important to note that at this stage, this ontology does not contain rules for reasoning.

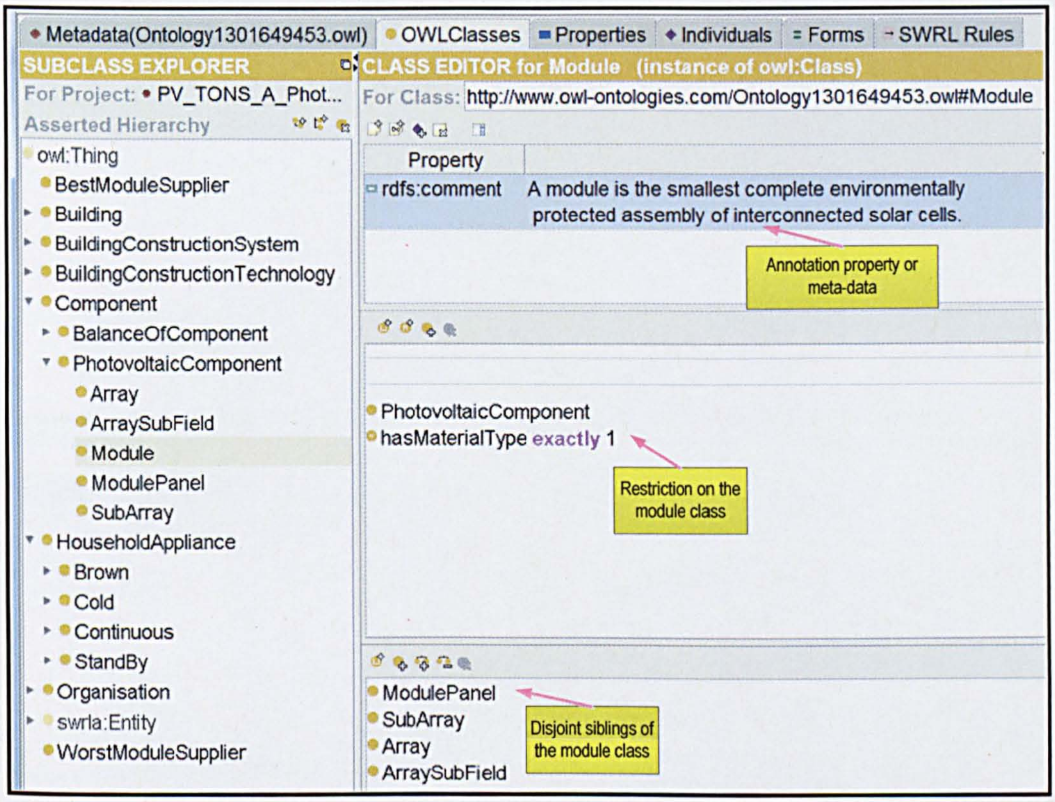

Figure 7.12. PV-system ontology in Protégé-OWL 3.4.4

For easy visualisation, Jambalaya is used in presenting the PV-system technology ontology as in Figure 7.13.

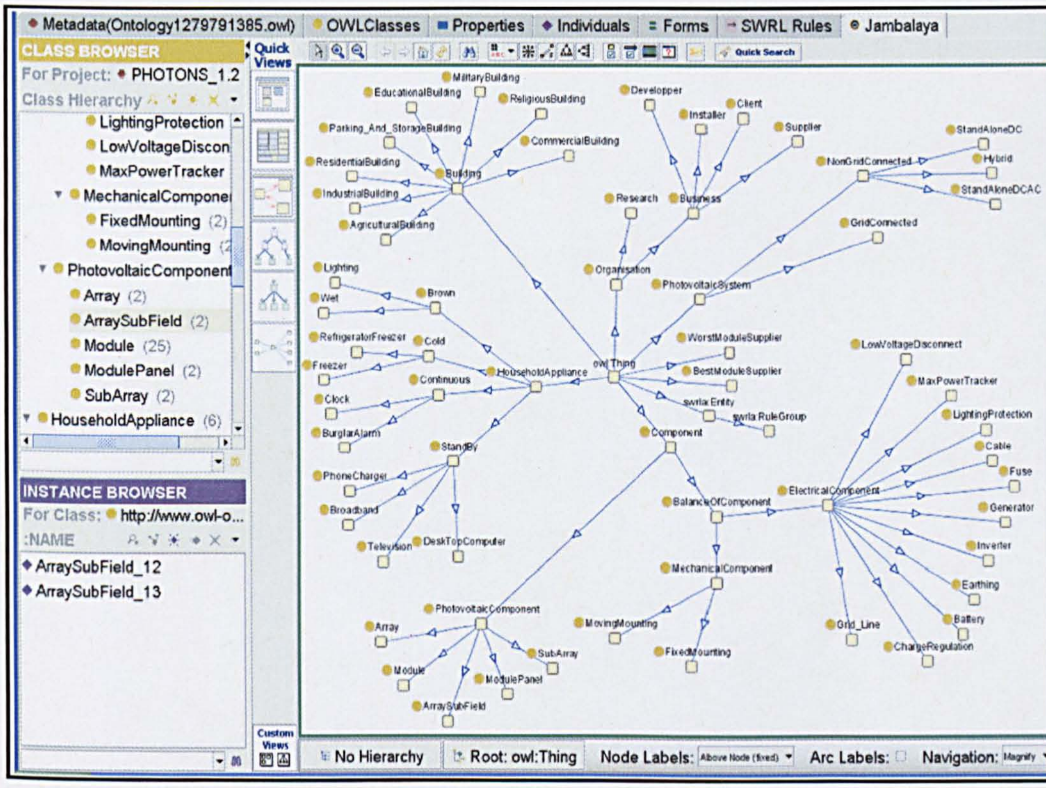

Figure 7.13. Graphical visualisation of the PV-system ontology

7.5.1.2 Implementation in a storage system

Based on the above implementations a complete PV-system ontology excluding rules is stored in usable forms. There are two forms of storing ontologies. The first technique for storing ontologies is to use the file system. Storage of ontologies in file formats is suitable for simple applications involving a single ontology developer. The main problem with this technique is that file systems do not provide persistency, scalability, and sharability (Astrova *et al.* 2007; Sane and Shirke 2009). The second technique entails the storage of the ontology in a database server which facilitates persistency, scalability, and sharability. In addition to providing the above advantages, storing ontologies in a database server provides a conducive environment for multiple users participating in the development of same or different ontologies. Based on the fact that only one developer (i.e. the author of this thesis) was involved in the development of PV-TONS system the file storage system was adopted. Thus, the PV-system ontology file was generated automatically with the aid of a conversion plug-in in Protégé-OWL. An abstract of the PV-system OWL file in RDF/XML syntax is presented in Figure 7.14 while the full file will be presented in Annex 7.1.

```
<owl:Class rdf:ID="StandAloneDC">
<rdfs:subClassOf rdf:resource="#NonGridConnected"/>
<owl:disjointWith rdf:resource="#Hybrid"/>
<owl:disjointWith rdf:resource="#StandAloneDCAC"/>
</owl:Class>
<StandAloneDC rdf:ID="StandAloneDC_10">
<isComposedOf rdf:resource="#Array_10"/>
<isComposedOf rdf:resource="#Battery_33"/>
</StandAloneDC>
<owl:Class rdf:ID="StandAloneDCAC">
<rdfs:subClassOf rdf:resource="#NonGridConnected"/>
<owl:disjointWith rdf:resource="#Hybrid"/>
<owl:disjointWith rdf:resource="#StandAloneDC"/>
</owl:Class>
<StandAloneDCAC rdf:ID="StandAloneDCAC_11">
<isComposedOf rdf:resource="#Array_11"/>
<isComposedOf rdf:resource="#Battery_36"/>
<isComposedOf rdf:resource="#Inverter_46"/>
</StandAloneDCAC>
<owl:Class rdf:ID="SubArray">
<rdfs:subClassOf rdf:resource="#PhotovoltaicComponent"/>
<rdfs:subClassOf>
<owl:Restriction>
<owl:onProperty rdf:resource="#isComposedOf"/>
<owl:someValuesFrom rdf:resource="#ModulePanel"/>
</owl:Restriction>
</rdfs:subClassOf>
<owl:disjointWith rdf:resource="#Array"/>
<owl:disjointWith rdf:resource="#ArraySubField"/>
<owl:disjointWith rdf:resource="#Module"/>
<owl:disjointWith rdf:resource="#ModulePanel"/>
</owl:Class>
<SubArray rdf:ID="SubArray_20">
<isComponentOf rdf:resource="#Array_10"/>
<isComposedOf rdf:resource="#ModulePanel_18"/>
</SubArray>
<SubArray rdf:ID="SubArray_21">
<isComponentOf rdf:resource="#Array_11"/>
<isComposedOf rdf:resource="#ModulePanel_19"/>
</SubArray>
<owl:Class rdf:ID="Supplier">
<rdfs:subClassOf rdf:resource="#Business"/>
<owl:disjointWith rdf:resource="#Installer"/>
</owl:Class>
```

Figure 7.14. Excerpts of PV-system OWL file

7.5.2 Implementation in the application logic layer

The main purpose of this section is to extract relevant parts from the PV-system ontology stored in the form of an OWL file on the local system. From a programming perspective, the Protégé-OWL and Jena APIs are a natural choice. Protégé-OWL and Jena APIs are quite common and are the main programming APIs often used in the manipulation of ontologies in semantic web environments. However, a more simplified and powerful language such as the SQWRL developed mainly for manipulating ontologies is more appropriate and an easier solution. Also, partly because SQWRL has been developed for SWRL rules which have been included in PV-system ontology. Hence, SQWRL was used in this study. However, before examining the rationale behind the different rules and how they were constructed it is important to first of all highlight the weakness of manipulating ontologies using basic OWL properties.

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. The union, intersection, negation operators and property restrictions form the foundation of the DL, the basis of computational complexity of most OWL reasoners including Pellet 1.5.2 as used in this study. Although the use of these operators in the formation of queries to interrogate any ontology in OWL is now too common, it is still very limited in reasoning on real life applications (Walton, 2007). Consequently, an extension of OWL is undertaken to include a popular rule language called SWRL. The SWRL was used in editing rules that enhanced reasoning in the PV-system ontology. This was undertaken using the SWRL plug-in called SWRLTab incorporated in Protégé-OWL 3.4.4. The execution of SWRL rules requires a functional rule engine. The rule engine can perform reasoning using a set of rules and a set of atoms as input. In this study the Jess rule engine - the most efficient and compatible with Protégé-OWL was adopted. The translations required to run SWRL rules in Protégé-OWL represented in the database layer in Figure 7.1 is explained in the ensuing paragraphs. This is facilitated by an excerpt from Figure 7.1 represented in Figure 7.15.

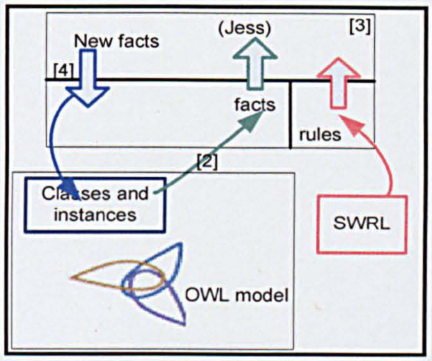

Figure 7.15. Actions for the SWRL rules in Jess

The rules are edited in SWRLTab, and introduced in the rule engine (1). Afterwards, the ontology and the knowledge base are translated and introduced into the Jess rule engine (2). After reasoning (3), the results are translated back into the OWL model in Protégé-OWL (4). This process is continuous until new facts are no longer generated.

The SWRLTab syntax used are the conjunction symbol, the implication symbol, the rule variables, the individual syntax, class atomic syntax, individual property atoms syntax and data property atoms and SWRL built-ins. The conjunction syntax is denoted as Λ and the implication symbol as→ . The rule variables are represented by the interrogation idenfier **?,** e.g ?x. The class atoms are constructed from an OWL class named followed by one variable or individual name in parenthesis, e.g PV-array(?x). The individual property atoms are constructed from an OWL object property name followed by two arguments in the paranthesis, e.g. hasConversionEfficiency(?x, ?y). In like manner, the data property atoms are represented in the same way as individual property atoms. Some examples of SWRL built-ins used in this study are sqwrl:lessThan(?a, m), sqwrl:moreThan(?b, n) and means that the rule variables a and b are less than m and greater than n where m and n are real numbers respectively. The sqwrl:select(....), is a built-in that select rule variables. In the ensuing sections, the application of the SWRL syntax will be used in implementing the rules elicited in Chapter 6. This rules will be presented exactly as it would have appeared in SWRLTab plug-in.

Rule 7.1. Concept classification rule

In Chapter 6, one of the rules for classifying highly efficient PV-modules was presented as:

If (a PV-module has conversion efficiency greater than 0.8)
Then (classify the PV-module as highly efficient) r-7.1

In order to facilitate understanding the above rule will be broken into two main parts - the antecedent and the consequent. The antecedent can be broken into three parts, the PV-module concept, the conversion efficiency concept and the constraint concepts (i.e. conversion efficiency greater than 0.8). The PV-module concept is modelled as a class atom PV-module (?p) such that the variable *p* represents instances of the PV-module. The conversion efficiency is modelled as a data-type atom. This is represented as hasConversionEfficiency(?p, ?e), meaning a given PV-module instance *p* has a conversion efficiency *e*. The constraint on conversion efficiency is modelled using the standard SWRL built-in function sqwrl:greaterThan. This is represented as sqwrl:greaterThan(?, 0.8) , the conversion efficiency is greater than 0.8.

The consequent of rule r-7.1 implies that if the conversion efficiency of PV-modules are greater than 0.8 then classify the instances as highly efficient. This consequent is modelled as a class atom represented as HighlyEfficient(?p). By using the conjunction symbol Λ the antecedent of rule r-7.1 is combined as PV-module(?p) Λ hasConversionEfficiency(?p, ?e) Λ sqwrl:greaterThan(?e, 0.8). The implication arrow is used to link the antecedent and consequent as presented in rule r-7.2.

Rule 7.2. Modelling rules using SWRL

PV-module(?p) Λ hasConversionEfficiency(?p, ?e) Λ r-7.2
sqwrl:greaterThan(?e, 0.8)→ HighlyEfficient(?p)

What this means is that if there is a PV-module p and that PV-module has an efficiency e such that the e is greater than 0.8 then classify the PV-module as an HighlyEfficient.

Likewise a query for finding the different PV-module names using the sqwrl:select built-in can be modelled as in query q-7.1.

Query 7.1. PV-module name selection rule

PV-module(?p) ∧ hasName(?p, ?name) →sqwrl:select(?name) q-7.1

Query q-7.1 means if there is a PV-module p and the PV-module has a name then select the name.

One example of a rule in the PV-system ontology rule-based system that will be explained in detail is the rule depicting the computation of the module size in a PV-system. The rule is stated below and captured in the SWLRLTab as rule r-7.3.

Rule 7.3. Generic rule for the sizing of PV-modules

If <<**annual** energy load is known and the energy efficiency >> **Then** <<size the module>> r-7.3

Although the above rules appear too simple to be generated using a combination of SWRL syntaxes, in reality it is more complex and challenging. In fact, it depends on some object-oriented techniques (e.g. composition relations) and OWL philosophy (open world and closed world reasoning). These object-oriented techniques and OWL philosophy have been used in constructing SWRL rules and SQWRL queries that have been included in the PV-system ontology. This constitutes a semantic web prototypical system PV-TONS referred to in this study. Due to space and by virtue of the fact that rule and query formats in SWRLTab are more compact, all the rules in PV-TONS cannot be explicitly modelled and explained as done with rule r-7.1 and query q-7.2. However, a few exemplary rules and queries with their explanations have been presented in Table 7.2. Also, the entire rules and queries in PV-TONS cannot be viewed in a simple snapshot; a partial snapshot is presented in Figure 7.16 while the details of the rules and queries edited in SWRLTab can be found in the PV-TONS OWL file in Appendix 7.1.

Table 7.2. Examples of rules and queries in PV-TONS

Rules and queries	Application
tbox:isDirectSubClassOf(?subClass, HouseholdAppliance) → sqwrl:select(?subClass)	Retrieval of all the different types of household appliance in a building
tbox:isDirectSubClassOf(?subClass, Building) → sqwrl:select(?subClass)	Retrieval of all the building types where PV-systems can be integrated
tbox:isDirectSubClassOf(?subClass, PhotovoltaicSystem) → sqwrl:select(?subClass)	Retrieval of all the PV-systems that can be used in a building
tbox:isDirectSubClassOf(?subClass, Component) → sqwrl:select(?subClass)	Retrieval of all the different components in a PV-systems
PhotovoltaicComponent(?x)∧hasEnergyEfficiency(?x,e)→sqwrl:select(?x,e)	Determination of the different energy efficiencies of the different PV-system components
PhotovoltaicSystem(?x) ∧ isComposedOf(?x, ?z) ∧ isSuppliedBy(?x, ?y) ∧ sqwrl:orderBy(?x) → sqwrl:select(?x, ?y, ?z)	Determination of the different components of PV-system and their corresponding suppliers, with a further constraint on the results output to be ordered according to the different PV-systems.
Module(?x) ∧ hasSustainabilityIndex(?x, ?a) ∧ sqwrl:makeSet(?s, ?a) ∧ sqwrl:max(?max, ?s) ∧ swrlb:equal(?a, ?max) ∧ hasCapitalCost(?x, ?y) ∧ hasAnnualCostSaving(?x, ?z) → sqwrl:select(?x, ?a, ?y, ?z)	Determination of the module maximum sustainability index and hence the deduction of the capital cost and annual cost saving of the module.
Module(?x) ∧ hasNominalPowerOutput(?x, ?y) ∧ hasSustainabilityIndex(?x, ?b) ∧ hasConversionEfficiency(?x, ?z) ∧ Inverter (?a) ∧ hasNominalPowerOutput(?a, ?e) ∧ HouseholdAppliance(?g) ∧ hasPowerRating(?g, ?h) ∧ swrlm:eval(?area, "y/z", ?y, ?z) ∧ swrlb:equal(?e, ?y) ∧ swrlb:greaterThan(?y, ?h) ∧ sqwrl:makeSet(?s, ?h) ∧ sqwrl:sum(?sum, ?s) → sqwrl:select(?x, ?area, ?a, ?b, ?e) ∧ sqwrl:select(?sum)	The sizing of a PV-system module
Component(?x)∧ isSuppliedBy(?x, ?y)∧ isComposedOf(?x, ?z)→sqwrl:select(?x, ?y, ?z)	Determination of the different constituents of the different components of a PV-system
Module(?x) ∧ isSuppliedBy(?x, ?y) ∧ hasSustainabilityIndex(?x, ?a) °sqwrl:makeSet(?s, ?a) °sqwrl:max(?max, ?s) ∧ swrlb:equal(?a, ?max) → BestModuleSupplier(?y)	Classification of the best suppliers of PV-system modules
BestModuleSupplier(?y) → sqwrl:select(?y)	Determination of the best suppliers of PV-system module
BestModuleSupplier(?y) ∧ hasOrganisationBuildingLocation(?y, ?x) → sqwrl:select(?y, ?x)	Determination of the location of the best PV-module supplier
Module(?x) ∧ isSuppliedBy(?x, ?y) ∧ hasSustainabilityIndex(?x, ?a) °sqwrl:makeSet(?s, ?a) °sqwrl:min(?min, ?s) ∧ swrlb:equal(?a, ?min) → WorstModuleSupplier(?y)	Classification of the worst suppliers of PV-system modules
WorstModuleSupplier(?y) → sqwrl:select(?y)	Determination of the worst suppliers of PV-system module
WorstModuleSupplier(?y) ∧ hasOrganisationBuildingLocation(?y, ?x) → sqwrl:select(?y, ?x)	Determination of the location of the worst PV-module supplier

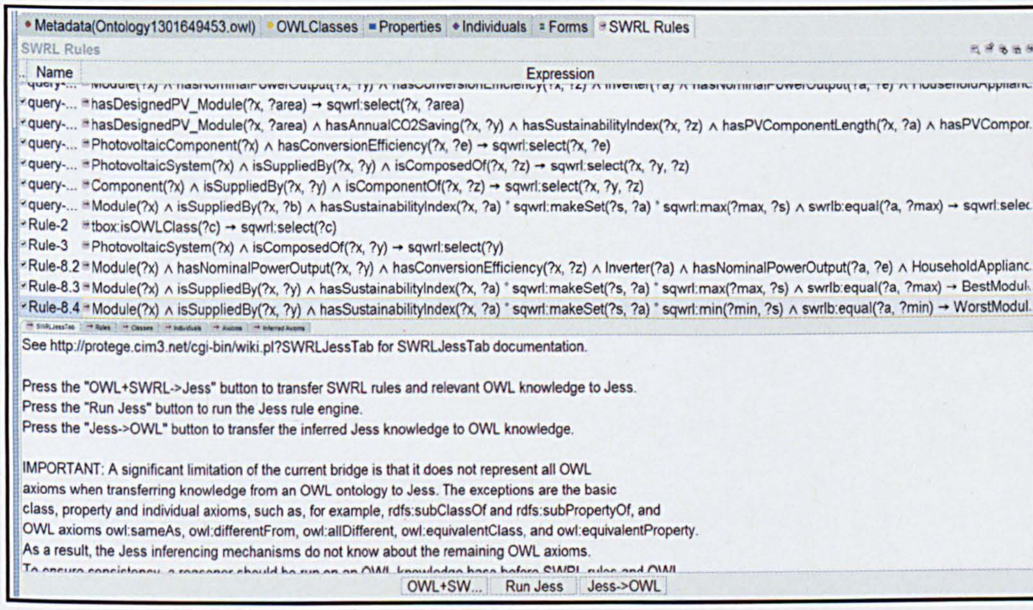

Figure 7.16. Sample SWRL rules and queries in PV-TONS

7.6 Conclusion

The chapter examined the design and implementation of the system prototype for this research. In presenting the prototype, a systematic approach was pursued. The definition of the system requirements, the configuration of different software components, the design of the system architecture and the system implementation were respectively adopted.

System requirements are essential as they outline the functions to be performed by the system prototype. The configuration of the different software components is important as they enable the achievement of the system requirements. The system architecture graphically displays the required components and links among them in the system prototype. The system architecture is very useful as it provides a reference point for implementation. The "Ontology Development 101" was adopted in the implementation of the prototype.

The system prototype is an integration of the Protégé-OWL 3.4.4 as an OWL ontology modelling tool, SWRLTab as a rule base, Jess engine as a reasoning engine and Pellet 1.5.2 for the syntactic verification of the prototype. The key activity of the implementation in the integrated software environments are the transformation of the sustainable building technology and PV-system UML knowledge in Chapter 6 to OWL using techniques proposed in Berardi *et al.* (2005), Dong *et al.* (2007), Brockmans *et al.* (2004) and Gašević *et al.* (2004); enrichment of the prototype with OWL restrictions; extension of the OWL knowledge to include rules; population with instances and validation with reasoners.

From an ontological perspective, two main ontology knowledge models have been generated. Firstly, sustainable building technology ontology; and secondly the PV-system ontology, a particular type of sustainable building technology ontology. However, it is important to establish whether the prototype system in this chapter can be used in demonstrating the purpose for which it was developed. This is investigated in Chapter 8, where semantic and syntactic validation is undertaken to ensure the correctness of the prototype system. Furthermore, after the semantic and syntactic validation, a case study application will be employed to validate the prototype system.

8. SYSTEM EVALUATION

8.1 General

The design and implementation of the PV-TONS prototype system was presented in Chapter 7. The implementation in the different software settings such as implementing the ontology in a storage environment, implementing in an ontology editor and implementing the ontology in a reasoning environment were also presented. In order to ensure PV-TONS is fit for use in a practical setting, it is necessary to evaluate it in its different environment (i.e establish if PV-TONS fulfils design requirements). To achieve this task, it is important to re-visit one of the investigative questions highlighted in Chapter 5; i.e. "How can knowledge about PV-systems be easily accessed from PV-TONS?" In order to efficiently manipulate PV-system knowledge it is important that the PV-TONS ontology is well structured both syntactically and semantically fit for use in a practical or real-world setting. Having established the semantic correctness using the PROMPT alignment/merging techniques by Noy and Musen (2003) this chapter will in the first instance establish the syntactic correctness of the PV-TONS. Secondly, the chapter validates PV-TONS with a case study. The main objective of this case study is to establish whether PV-TONS does what it is intended to do or produces meaningful results when queried.

8.2 Semantic, syntactic and OWL language compliant verification of the PV-TONS

Chapter 6 verified semantically the PV-system ontology. The implementation of this ontology in a software environment as was the case in Chapter 7 means semantic and syntactic errors or anomalies are likely to occur. An example of a semantic error may be the editing of a given class under a concept where it was not intended to be. On the other hand, an example of a syntactic error may be the incompatibility of a data-type with its value. Therefore, it is important to further conduct semantic and syntactic verification to render the PV-TONS free of anomalies. Common ontology plug-ins that have been used in this process include OWL Ontology validator, Run ontology test, and Pellet reasoner. After verification, the ontology is checked to ensure it is OWL compliant. The PV-TONS system is finally validated with the use of a case study.

8.2.1 Semantic and syntactic verification of design anomalies

The last activity in an ontology knowledge base project is that of ensuring the knowledge base is free of anomalies (Antonio and van Harmelen, 2004). In the design process of ontologies, anomalies can often be committed and often there is a need for the anomalies to be fixed for the ontology to be explored. Common ontological activities such as ontology merging and extending ontologies to include rules are likely to generate anomalies (Baumeister *et al.*, 2007). The three common types of design anomalies often mentioned in the literature are the inconsistency, incompleteness and redundancy (Gómez-Pérez, 2001).

There are three main types of design anomalies that cause *inconsistency* in an ontology during reasoning. These are circulatory, partition and semantic errors. Circulatory errors occur when a class is defined as a subclass or superclass of itself at any level of hierarchy in an ontology. For example, defining BalanceOfComponent as a subclass of ElectricalComponent leads to a circulatory inconsistency as ElectricalComponent is already a subclass of BalanceOfComponent (see Figure 6.9). Partition errors occur when ontologist omit important axioms or information about the classification concept, reducing the reasoning power and inferring mechanisms (Gómez-Pérez, 2001). An example of a partition error will occur if in modelling the PV-system ontology of Figure 6.9, the Cable is defined as a subclass of ElectricalComponent and MechanicalComponent without having defined the disjoint axiom between the ElectricalComponent and MechanicalComponent classes. Semantic errors occur when ontologists make an incorrect class hierarchy by classifying a concept as a subclass of a concept to which that concept does not really belong. An example of a semantic inconsistency is the classification of the GridConnected class to be the subclass of the NonGridConnected class of the UML PV-system ontology of Figure 6.9.

The *incompleteness errors* do occur when relationships between ontological concepts are imprecisely defined. Incompleteness creates ambiguity and hinders reasoning that can be conducted through the use of reasoners. For example, in the PV-system ontology, the PhotovoltaicSystem concept is incompletely classified by ignoring the NonGridConnected and GridConnected systems which are types of PV- systems.

The *redundancy errors* occur when particular information is inferred more than once from the relations, classes and instances found in the ontology. In other words, a redundant knowledge is defined as ontological definitions or rules that can be removed from the ontological knowledge base without changing the intended semantics (Baumeister *et al.*, 2007). An example of a frequent redundant knowledge occurs during the combination of rules and ontology. This will be examined below.

Rule 8.1. Redundancy in rules

If A, A_i are either class or property atoms, and that the rules

$A_i \rightarrow A$ for some A_i, i=1...n. 8.1a

$A_1 \wedge A_2 .... \wedge A_n \rightarrow A$ 8.1b

8.1a and 8.1b are in the same rule-base, then one of them is redundant.

8.2.1.1 Checking ontology inconsistencies, redundancies and incompleteness

Protégé-OWL provides a test framework which contains various test plug-ins that may be run on the ontology during or after development to detect inconsistencies, redundancies and incompleteness. Two of these plug-ins commonly used are the "Run Ontology Test" and "Pellet 1.5.2" in Protégé-OWL 3.4.4. During the development of the PV-TONS ontology in Protégé-OWL 3.4.4 these plug-ins were used interchangeably. This was to ensure consistency in the results. The use of these tools in the verification process was incremental and continuous so as to avoid the propagation of errors. After running each of the plug-ins, the results are displayed in a pop-up pane at the bottom of the Protégé-OWL screen. The test results pane is presented as follows:

- *Type*: the type of test result (a warning! and error! etc.);

- *Source*: the source of the test result (e.g. a class or property);

Double clicking on the *source* will automatically navigate to the sources of errors, by automatically selecting a class on the 'OWLClasses' tab, or a property on the 'Properties' tab for example.

- Test Result: a message that describes the result is obtained.

In some cases Protégé-OWL is able to modify/correct/repair aspects of the ontology that the tests have found to be at fault. The "Run Ontology Test" and the "Pellet 1.5.2" were constantly used during the development of the PV-TONS system until a final product, free of errors was obtained. The syntactic verification of the PV-TONS system results is presented in Figure 8.1.

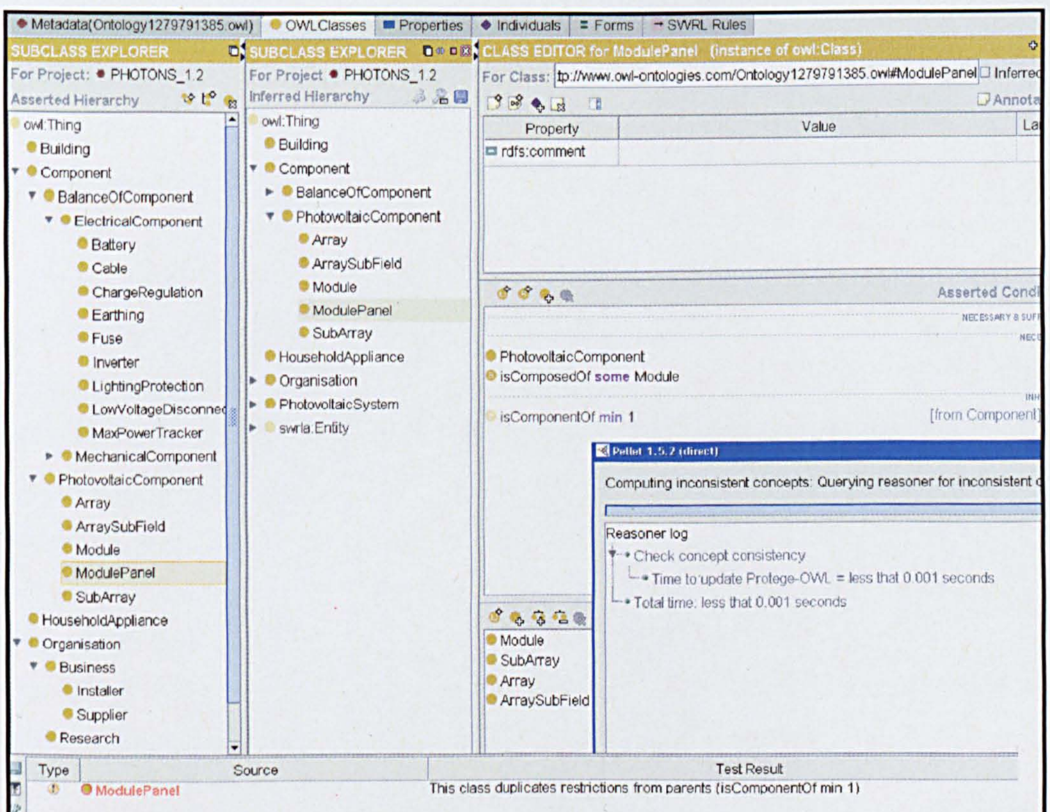

Figure 8.1. Checking of anomalies in PV-TONS system

The error message which is linked to the "ModulePanel" indicated in red reads "This class duplicates restriction from parents isComponentOf min 1". The error message is fixed by manually taking off one of the "ModulePanel" and then re-running the Pellet

1.5.2 reasoner again. No errors emerged and the ontology is said to be complete and free of anomalies and thus said to be syntactically validated. However, in practice after an ontology has been developed and anomalies checked and semantically verified, temporal or permanent classes are introduced into the ontology to test whether the ontology was correctly built (Horridge *et al.* 2007; Horridge and Patel-Schneider 2008). The introduced concepts are often called probe classes. A probe test (Horridge and Patel-Schneider, 2008) aims to test an ontology design by deliberately introducing predictable faults to the ontology and then observing 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 that requires them and not specifying them where they are not necessary. Based on the OWL open world reasoning OWL classes "overlap" until they have been stated to be disjointed from each other (Horridge and Patel-Schneider, 2008). If certain classes are not made disjointed from each other, then unexpected results can arise. Accordingly, if certain classes have been incorrectly made disjointed from each other, then this can also give rise to unexpected results.

Based on the literature review on PV-system, it emerged that some concepts should be made disjointed with respect to others and some should not be made disjointed. This makes the probe test for disjointedness imperative in this study. As an example for a probe test for disjoint axioms, a concept such as "BalanceOfComponent" with subclasses as "mechanical component" and "electrical component" are clearly disjoint. These subclasses are clearly disjoint because both cannot have a common instance, or even common subclasses. From Figure 6.9, 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 description logic reasoner will not detect that an instance of a "battery" cannot be an instance of a "cable".

To test if the disjoint axiom was defined in the "BalanceOfComponent" concept, a new concept called "ProbeInconsistencyBalanceOfComponent" was introduced as a subclass of the "mechanical component" and also as a subclass of the electrical component. Next an anomaly test was conducted using Pellet 1.5.2 as explained above. There was an inconsistency error message for "ProbeInconsistencyBalanceOfComponent" in the test result and the "ProbeInconsistencyBalanceOfComponent" was then removed. If the inconsistency error message had not occurred, then the disjoint axiom specifications in the "mechanical" and "electrical" components would have been defined and the probe test re-conducted until the test result is free of errors. Once the test result is free of errors, then the probe class is removed.

As earlier mentioned in section 2.3.4.2, a non-grid-connected system can be a stand-alone DC, a stand-alone DC-AC, or a hybrid of both. Their respective main components are a battery, charge controller and a PV-array for a stand-alone DC; a battery, charge controller, DC-AC inverter and PV-array for a stand-alone DC-AC system; a battery, charge controller, DC-AC inverter, system controller, battery controller and generator for a hybrid system. This means that in modelling the classes stand-alone DC; stand-alone DC-AC and hybrid as types of classes in an OWL ontology editor environment, these classes 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 classes, the "ProbeInconsistencyBalanceOfComponent" is introduced as subclasses of these classes and the reasoner Pellet 1.5.2 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 and needs to be removed and the reasoner Pellet 1.5.2 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 classes with instances, no error message will emerge if same instances appear to two or more classes that have not been specifically made disjoint. After the semantic and syntactic verification the ontology is verified for language compliance. In this case it is verified against OWL language compliance since this is the language used in developing the ontology. This is examined in the ensuing section.

8.2.1.2 Verification for ontology compliance with the web ontology language

Although the PV-system ontology was developed using the OWL, it is important to verify its compliance to OWL language syntax by using automatic techniques. This was undertaken using the Manchester OWL syntax validator. The OWL validator accepts ontologies written in RDF/XML, OWL/XML, OWL Functional Syntax and Manchester OWL Syntax. The result for the OWL compliance test was successful and is presented in Appendix 8.1.

Having verified the prototype system, it is necessary to test the system with real data instead of simulated data (Sommerville, 2007). Like in the use of case studies for evaluation in social sciences (Yin, 2009), a real-world case study has been used to validate the prototype system. In other words, validation here will seek to establish if the prototype will do what it was intended to do.

8.3 Validation of the PV-TONS using a case study

In Chapter 7 it was established that PV-TONS is designed to facilitate the design and selection of PV-systems and its components. Therefore, its validation will seek to take readers through the design and selection process of PV-systems and its components. A description of the case study is presented in the ensuing section.

8.3.1 Description of the case study

For the purpose of this study, a sustainable building that uses a PV-system as its power source has been selected. The Oxford solar house, a classic example that uses PV-system as its power source has been chosen in this study. The reasons for this choice are twofold. Firstly, the methodology for the design and selection of PV-system components for the house is the same methodology implemented in PV-TONS. Secondly, the selected project has most documentation to facilitate a detailed abstraction of the various resources needed to validate PV-TONS. However, the PV-system supplier's attributes are extracted from different secondary sources, and used to populate the PV-TONS system.

The Oxford solar house is the first house in the UK designed to maximise energy efficiency with a fully integrated PV roof. The house was designed by Susan Roaf, a former Professor of Oxford Brookes University, now a Professor at Heriot-Watt University. The house was built in 1995 and is located in a suburban street in North

Oxford. The Oxford solar house is a six bedroom family home. It produces only 130KgCO_2/annum/m², in contrast to comparable UK houses that produce 5 000Kg CO_2/annum/m². For illustrative purposes, the Oxford solar house is presented in Figure 8.2.

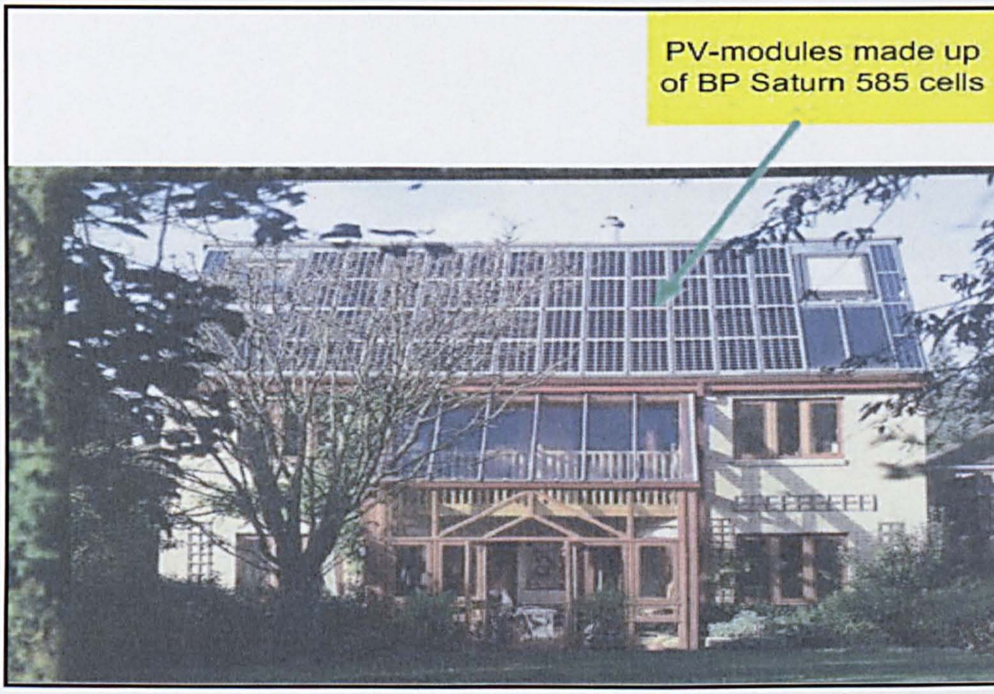

Figure 8.2. The Oxford solar house
[Source: Roaf *et al.*, 2001]

The design for the PV-array on the house was influenced by the following design considerations:

- The PV-system must be integrated in the house both technically and architecturally;

- The PV-system should have a peak power output of 4kW to ensure the house generates more electricity than it used over the year, based on the results of the load analysis done by Dichler (1994);

- The system should operate in a normal grid-connected mode with the grid providing back-up power when needed, for instance at night in winter or in poor whether condition.

The house receives about 4.0 peak sun hours in summer and only 0.6 peak sun hours in winter (Dichler, 1994). This constitutes a significant variation in output from winter to summer. Hence, the PV-array was designed to achieve a reasonable level of diurnal autonomy for the house for around nine months of the year.

It was estimated that in the summer months, the energy surpluses were around 12 kWh per day. This is greater than the energy deficit in winter and hence the PV-system was connected to the national grid utility to receive surpluses. The slope of the south-facing back roof was designed to be optimal for the generation of electricity from the PV-array at 39° from the horizontal. Rod Scott of BP Solar helped in choosing the best panels on the market, the robust monocrystalline, high-efficiency BP Saturn 585 cells. In total, 48 modules required a flat roof size of 6.8m x 5m and were arranged in four vertical rows of 12 modules in each row. Thus, with the optimal angle of tilt and these dimensions now available, it was possible to fix the ridge height of the building just above the top PV-panel, so deciding the slope of the north-facing roof as the ridge height was fixed.

Although in this project, the choosing of the best PV-module was done by an expert, Rod Scott of BP Solar, there is a high likelihood of things to go wrong. This is because, of huge number of different components in a PV-system, the availability of the different types of PV-system in the market, huge number of suppliers and the variability of the different parameters that are considered in the design of the PV-system such as household appliances, building site consideration and the different hours of the day. Furthermore, there is a challenge in deciding whether to compute the size of the PV-module or the PV-array. As depicted in Figure 2.2, PV-array consists of PV-modules assembled together and bonded by an external frame. The external frame is chosen by different suppliers or developers depending on their different interest. The external frame influences the overall efficiency of the PV-array and can influence design results of PV-systems. Also, most literature provides efficiencies of PV-modules and not PV-arrays. In this study, the choice was made to focus on PV-modules rather than on PV-arrays.

From the above analysis the task of choosing a PV-module for a building is highly complex and therefore presents a good environment to validate a semantic web system such as PV-TONS.

The task of choosing a PV-module requires that the PV-module should be designed to provide the energy required in a building. From the literature, the design of a PV-system translates to sizing its components so that it can provide the energy required by a building. The sizing of the different PV-system components often leads to non-standard sizes different from the sizes in the market which are often standardised. For example, the design of a PV-system for a building may lead to a requirement of $4.4m^2$ of PV-module to meet the building's electricity demand. However, in the market the available PV-module sizes are 1, 2, 3, 4, 5, 6 and $7m^2$. Choosing $4m^2$ will not produce the required electricity as it is below the designed size. A PV-module size of $5m^2$ will meet the building energy requirement although it may be slightly oversized. Given that a PV-system is made up of components and that these components may often be manufactured and supplied by different suppliers, when a given module is chosen, the corresponding component needs to be selected. Although, each of the components of the PV-system can be independently sized, in practice it is generally easier to size the PV-module and then select the other components.

After the description of the case study, it is important to specify how the knowledge concepts of the case study fit with PV-TONS and how the case study knowledge will be elicited and mapped into PV-TONS.

In Chapter 6, the UML knowledge model of PV-system knowledge model was developed and implemented in PV-TONS in Chapter 7. The task in this section will be to abstract knowledge about the Oxford solar house in away that fits with the PV-system UML knowledge model so that it can be easily implemented in PV-TONS. Three main literature sources were used. Firstly, the green book authored by the designer of Oxford solar house (Roaf *et al.*, 2001) was used. The second document, a peer-reviewed paper by Dichler (1994) was also explored. The third source of document, the PV-system supplier's website was explored. On analysing these documents the following challenges were encounted:

- While in the peer-reviewed documents and the green book by Roaf *et al.* (2001) use the terminology PV-array to mean a PV-panel ready for use in a building, factsheet from the PV-system supplier's website mostly talk about PV-module.

Also most information from the factsheets was related to PV-modules. This is the general practice in the industry. This practice is logical in the sense that PV-module properties are unique while PV-arrays properties may vary depending on other factors such as the way in which the modules have been assembled to form a PV-array. In the rest of this chapter, mostly information about PV-modules will be used and when information about PV-array is needed, it will be explicitly mentioned;

- Some of the information was not available. In cases where alternatives exist, they will be used if not a reasonable assumption is made.

The different literature sources cited above provided the bases to abstract knowledge concepts and data useful in modelling knowledge about the Oxford solar house. This is examined in the ensuing paragraphs.

Oxford solar house knowledge modelling

Based on analysis of the Oxford solar house literature, four main concepts emerged. These are the Oxford solar house building structure, the solar house PV-system, the supplier of the PV-system (BP Solar) and the concept of energy consumption by Oxford solar house building. These four concepts reflect the top level PV-system ontology previously defined in Chapter 6. In this regard, the Oxford solar house is considered an instance of the *Building* concept, the solar house PV-system is considered an instance of the *PhotovoltaicSystem* concept, BP Solar is considered an instance of the *Organisation* concept. The attributes of the solar house were abstracted from Roaf *et al.* (2001), Fuentes *et al.* (1996) and Dichler (1994). The attributes of the solar house PV-system and BP solar were abstracted from the PV-system fact sheet found on the BP Solar website. It is important to note that BP Solar is one of the accredited PV-system suppliers listed in the Green Book Live database used in this study. The different knowledge concepts about the solar house are presented in Table 8.1.

Table 8.1. Knowledge concepts identification

Name	Description	Value	Position in PV-TONS	Source
Instances				
Oxford solar house	This refers to the Oxford solar house building structure.	Not applicable	It is classified as an instance of the class *ResidentialBuilding*	Roaf *et al.* (2001), Fuentes *et al.* (1996) and Dichler (1994)
Oxford solar house PV-system	This refers to the PV-system set incorporated into the Oxford solar house building.	Not applicable	It is classified as an instance of a the class *GridConnectedSystem*	Roaf *et al.* (2001) and Dichler (1994)
BP 585	This is the PV-module which is component of the Oxford solar house PV-system.	Not applicable	It is an instance of the class *Module*	Roaf *et al.* (2001) and Dichler (1994)
BP Solar	This is the supplier of BP 585 module.	Not applicable	It is an instance of the class *Supplier*	Roaf *et al.* (2001), Fuentes *et al.* (1996) and Dichler (1994)
Inverter SMA 5kW	This is the inverter required to match the 4kW peak electricity of the Oxford solar house.	Not applicable	This is an instance of the class *Inverter*	Roaf *et al.* (2001), Fuentes *et al.* (1996) and Dichler (1994)
Data-type properties				
Warranty	This is the warranty of BP 585	25 years	This is captured under data-type property *hasWarranty*	BP Solar (2011b)
Module weight	This is the weight of BP 585	6.1Kg	This is captured under data-type property *hasComponent*	BP Solar (2011a)
Nominal power rating of BP 585	This is the nominal power rating of BP 585	85 W	This is captured under data-type property *hasNominalPowerOutput*	BP Solar (2011a)
Nominal power rating of Inverter	This is the nominal power rating of the Oxford solar house	5 kW	This is captured under data-type property *hasNominalPowerOutput*	Dichler (1994)
BP Solar experience	This refers to the number of years BP has been involved in PV-systems	40 years	This is captured under data-type property *hasBusinnessExperience*	BP Solar (2011c)
Maximum peak daily energy consumption	This refers to the maximum daily energy consumption by the Oxford	4kW	This is captured under data-type property *hasDailyPeakEnergyLoad*	Roaf *et al.* (2001), Fuentes *et al.* (1996) and Dichler (1994)
Module material type	This refers to the type of material BP 585 is made up off	Monocrystalline	This is captured under data-type property *hasMaterialType*	BP Solar (2011a)
Module conversion efficiency	This refers to the conversion efficiency of BP 585	14.5%	This is captured under data-type property *hasConversionEfficiency*	BP Solar (2011b)

Module dimension	This refers to the market dimensions of BP 585	1.197m X 0.53m	This is captured under data-type property *hasModuleDimension*	BP Solar (2011a), Roaf *et al.* (2001) and Dichler (1994)
Module area required	This refers to the computed area of BP 585 to provide energy to the Oxford solar house's roof	$28.57m^2$	This is captured under data-type property *hasModuleArea*	This has been calculated using peak daily energy and conversion efficiency
Annual CO_2 generation	This refers to the amount of CO_2 generated in a year by BP 585	$4870kgCO_2$/ annum/ m^2,	This is captured under data-type property *hasAnnualCO2Production*	Roaf *et al.* (2001), Fuentes *et al.* (1996) and Dichler (1994)
Annual CO_2 saving	This refers to the amount of CO_2 saved in a year by BP 585	$130kgCO_2$/ annum/ m^2	This is captured under data-type property *hasAnnualCO2Saving*	Roaf *et al.* (2001), Fuentes *et al.* (1996) and Dichler (1994)
Building location	This refers to the location of BP 585 supplier	Oxford	This is captured under data-type property *hasBuildingAddress*	Roaf *et al.* (2001), Fuentes *et al.* (1996) and Dichler (1994)
Object properties				
Module supplier	This refers to the supplier of BP 585	Not applicable	This is captured under object-type property *suppliesPhotovoltaicSystem* or *isSuppliedBy*	Roaf *et al.* (2001)
Building content	This refers to the relation between the Oxford solar house and the PV-system.	Not applicable	This is captured under the object-type property *hasContent* or *isContainedIn*	Roaf *et al.* (2001), Fuentes *et al.* (1996) and Dichler (1994)
PV-system-Supplier relationship	This refers to how the Supplier is related to the PV-System of the Oxford solar house	Not applicable	This is captured under object-type property *suppliesPhotovoltaicSystem* or *isSuppliedBy*	Roaf *et al.* (2001)
Composition relationships				
Oxford solar house inverter-PV-system	This refers to the composition relationship between the inverter and the Oxford solar house PV-system	Not applicable	This is captured under object-type property *isComposedOf* or *isComponentOf*	Roaf *et al.* (2001), Fuentes *et al.* (1996) and Dichler (1994)
Composition	This refers to the composition relationship between the PV-module and the Oxford solar house PV-system	Not applicable	This is captured under object-type property *isComposedOf* or *isComponentOf*	Roaf *et al.* (2001), Fuentes *et al.* (1996) and Dichler (1994)
Annotation properties				
Latest version of BP 585	This refers to the latest version of BP 585 in the market	BP 7180	This is captured under annotation properties	Mason *et al.* (2004)
Units of measurement	This referes to the different concepts units of measurement	Varies, as it depends on different properties	This is captured under annotation properties	Roaf *et al.* (2001), Fuentes *et al.* (1996) and Dichler (1994)

It is important to note that PV-TONS has already been populated with instances from the Green Book Live database. Hence, the solar house PV-system, BP 585 is an instance that is manually edited together with its properties. Other instances can be added to PV-TONS as well.

The design of PV-system for the Oxford solar house

Although the detailed design or sizing process of PV-system components is out of the scope of this thesis, the key steps involved in the design process will be used. The steps have emerged from the process map for the selection and design of PV-systems examined in Figure 6.7 (also see Tah and Abanda, 2011). They consist of the determination of the energy load of the building, the determination of the size of the PV-system module and the determination of the size of the different PV-system components (an inverter in the case of this study).

Determination of energy load of the building

In this study, the household energy appliance ratings were not available for the calculation of the building energy load. However, the daily energy load of the building provided in Dichler (1994) and Roaf *et al.* (2001) was used. This energy load value was 4kW. However, household appliance ratings have been included for alternative purposes and in cases where the calculated energy load values are not available, use can be made of the household appliance ratings in determining the daily energy load.

The sizing of the PV-module

Although given the daily energy load pattern of the building the different components can be sized, often only the PV-module is sized and the corresponding components are selected. This practice will be maintained in this study. The energy consumption pattern of a home does vary with respect to the different times of the day. There are times when the energy consumption is maximum (peak value), minimum or an average of the maximum and the minimum. It is the designer's choice to decide which type of daily energy load to use in the sizing of a PV-system. Any of the decisions have both economic and technical implications. For example, if a PV-system is designed with a peak energy load, then a grid-connected system may be required to tap the excess energy produced by the PV-system. This also means the PV-system may be oversized and hence may be expensive. On the other hand, if a PV-system is designed with a minimum daily energy load, technically a battery is required to store energy for future use. Although the PV-system may be under-designed and hence cheap, the additional cost of the battery needs to be taken into account. In the case of the Oxford solar house, the peak daily energy load was used. According to Roaf *et al.* (2001), the PV-module is sized by dividing the peak daily load of building by the module efficiency. The mathematical division operation has been included in PV-TONS using one of the SWRL built-ins functions. Once the peak daily energy load of a PV-system is entered the PV-module size is automatically determined.

The sizing of Oxford solar house PV-system components

As earlier mentioned after the sizing of the PV-module other components are sized. As an example, the sizing of an inverter is considered in this study. An inverter is needed in most residential PV-systems to convert the DC power from the PV-module to AC power suitable for the building. The inverter size will depend on whether the peak building energy load is going to be matched.

The above Oxford solar house knowledge concepts and its design process knowledge were manually input in PV-TONS and the four screenshots depicting the most important aspects are presented in the ensuing paragraphs. These aspects are the Oxford solar house building concept (Figure 8.3), the Oxford PV-system concept (Figure 8.4), the solar house PV-module (Figure 8.5) and the inverter (Figure 8.6).

Oxford solar house building concept

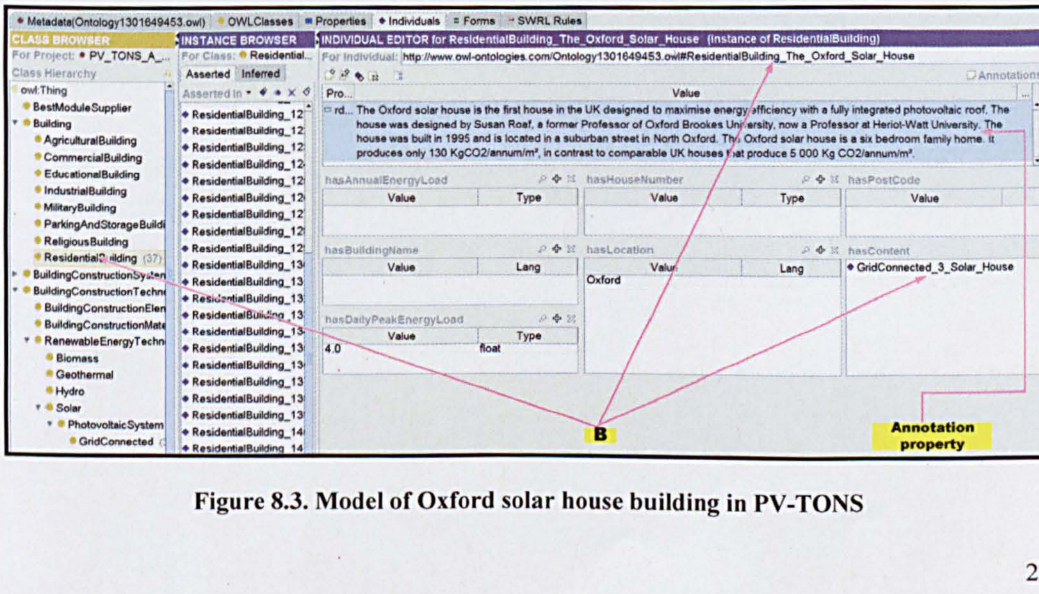

Figure 8.3. Model of Oxford solar house building in PV-TONS

In Figure 8.3 the annotation property provides a brief discussion of the Oxford solar house. The arrow B depicts the relation between the the Oxford solar house and the object property *hasContent*. The arrow B shows that the Oxford solar house named *ResidentialBuilding_The_Oxford_Solar_House* is an instance of the class *ResidentialBuilding* which is a subclass of *Building*. It also shows that the instance *ResidentialBuilding_The_Oxford_Solar_House* contains (related through the object property *hasContent*) a PV-system called *GridConnected_3_Solar_House*. Other properties include *hasHouseNumber, hasLocation, hasAnnualBuildingEnergyLoad, hasBuildingName, hasPostCode* and *hasDailyPeakEnergyLoad* as data-type properties.

The Oxford PV-system concept

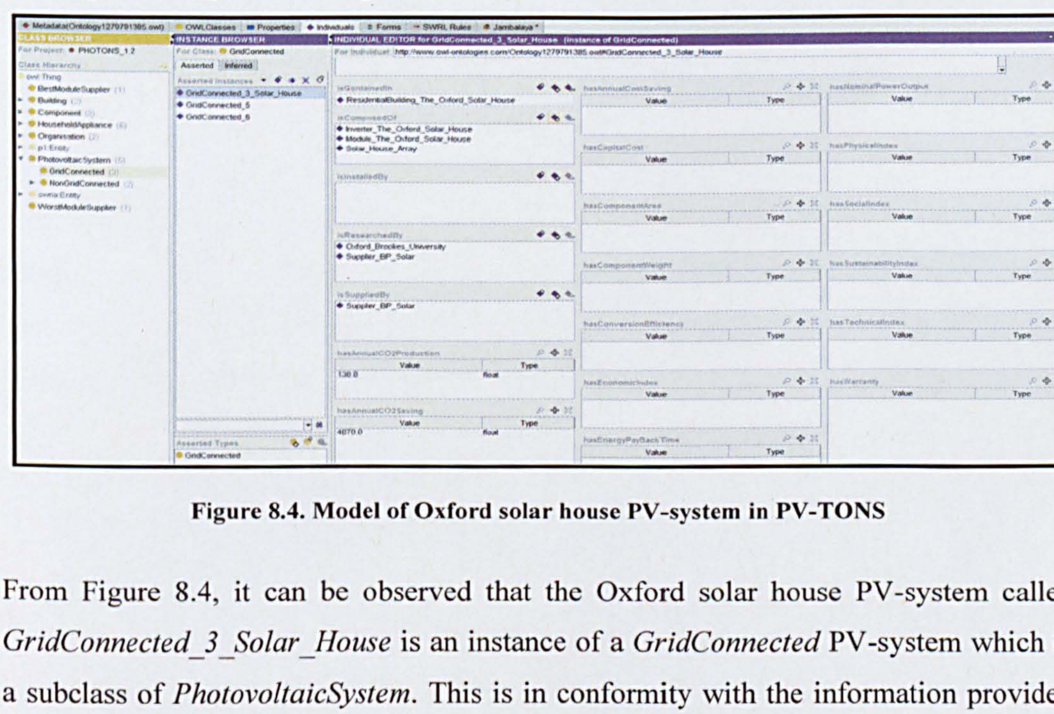

Figure 8.4. Model of Oxford solar house PV-system in PV-TONS

From Figure 8.4, it can be observed that the Oxford solar house PV-system called *GridConnected_3_Solar_House* is an instance of a *GridConnected* PV-system which is a subclass of *PhotovoltaicSystem*. This is in conformity with the information provided in Roaf *et al.* (2001). It also shows that *GridConnected_3_Solar_House* is contained (*isContainedIn*) in the Oxford solar house called *Residential_The_Oxford_Solar_House*. Furthermore, the different components of the *GridConnected_3_Solar_House* are provided through the *isComposedOf* composition property.

The solar house PV-module

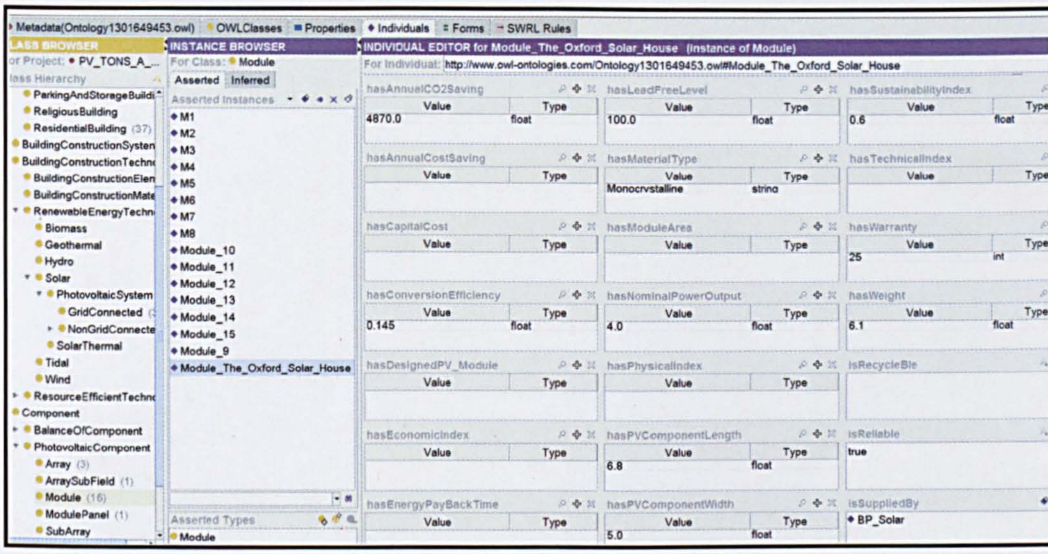

Figure 8.5. Model of Oxford solar house PV-module in PV-TONS

From Figure 8.5, it can be observed that the Oxford solar PV-module named *Module_The_Oxford_Solar_House* is an instance of the *Module* class which is a subclass of the *PhotovoltaicComponent*. The object and the data-type property values of the *Module_The_Oxford_Solar_House* can be edited under the different property headings or placeholders on the right of Figure 8.5.

The Oxford solar house inverter

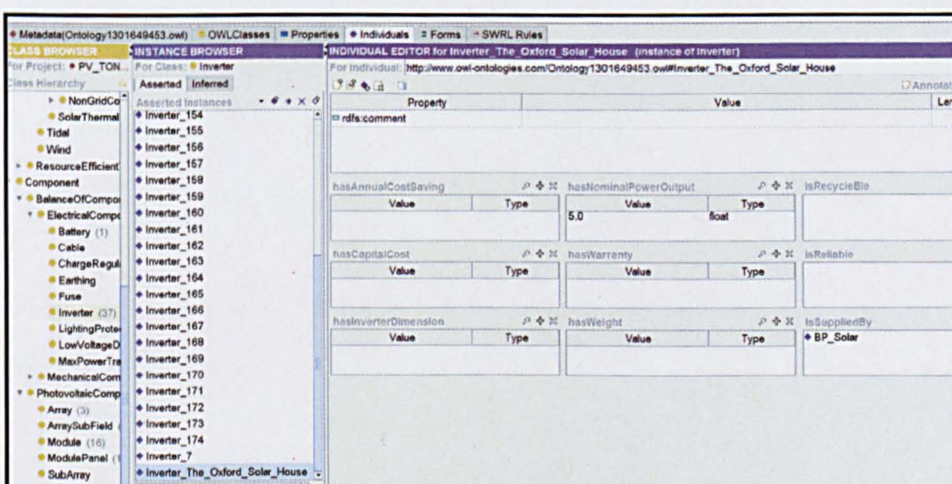

Figure 8.6. Model of Oxford solar house inverter in PV-TONS

From Figure 8.6, it can be observed that the Oxford solar house inverter named *Inverter_The_Oxford_Solar_House* is an instance of the *Inverter* class which is a subclass of the *ElectricalComponent*. The object and the data-type property values of the *Inverter_The_Oxford_Solar_House* can be edited under the different property headings or placeholders on the right of Figure 8.6.

One of the main goals of this study was to investigate the existing semantic web technologies that can be used in rendering information accessible to end-users. Its focus was to develop a semantic web-based application for retrieving (accessing and querying) the content of PV-TONS located on a local system. In section 8.3.1 a case study has been used to illustrate how knowledge about the case study is edited in PV-TONS. Although only a single case study was considered (in ontology terms it is an instance of a building), many other instances have been included in PV-TONS. This further adds to the complexity of reasoning and further justifies the reason for an ontology knowledge-based system. In the ensuing sections, an investigation will be conducted to establish if the query results from PV-TONS particularly with respect to the case study will provide meaningful answers. Answers from queries related to the case study are extremely important as they will be compared with those from the designer's documents. The investigation will be conducted in two stages. The first deals with the design and selection of PV-systems of the Oxford solar house. The second deals with other generalised queries that can be used in the design and selection of other PV-systems and components.

8.3.2 The design and selection of PV- system application

8.3.2.1 The design and selection of PV-system for the Oxford solar house

The first step in the design process is to determine the peak daily energy load of the Oxford solar house. This can be done from the analysis of household energy appliances' rating or monthly energy bills. None of these were available for use in this case study. However, it was highlighted that any PV-module of 4kW will meet the energy requirement of the Oxford solar house (Roaf *et al.*, 2001). Hence, the peak daily energy load of 4kW was assumed. This choice is the worst case scenerio, for any market PV-module with nominal energy load of 4kW will provide energy to any building of peak daily energy of less than or equal to 4kW. Having obtained the peak daily energy load, it is now certain that a PV-module of nominal energy load of 4kW will provide sufficient energy for the building, the conversion efficiency of the PV-module is chosen. The conversion efficiency was not available. However, a conversion efficiency of the BP 7180, the latest version of BP 585 module (Mason *et al.*, 2004) was obtained from the BP solar website and used. BP 7180 has conversion efficiency of between 14-15%. We assumed 14.5% in this study. The next stage is how to determine the appropriate size of the required PV-module. According to Roaf *et al.* (2001) the peak daily energy load should be divided by the conversion efficiency of the PV-module. In chapter 7, this has been modelled using the SWRL built-in and is represented as *swrlm:eval(?area, "g/z", ?g, ?z)*. The second design requirement involves the constraint that the nominal power load of the inverter should be at least equal to the nominal load of the PV-module. This constraint has been modelled using *swrlb:greaterThanOrEqual*. The function for computing module areas and the constraint are combined with other SWRL syntax to form an SWRL rules and the SQWRL is employed in supporting OWL queries. For example, in query q-8.1, SWRL built-ins constraints and syntaxes have been combined in a query that computes the size of a PV-module and corresponding PV-system components such as an inverter.

Query 8.1. Design and selection of PV-modules for the Oxford solar house

Building(?f) Λ Module(?x) Λ hasNominalPowerOutput(?x, ?y) Λ Inverter(?a) Λ hasNominalPowerOutput(?a, ?e) Λ hasDailyPeakEnergyLoad(?f, ?g) Λ swrlb:greaterThanOrEqual(?y, ?g) Λ hasConversionEfficiency(?x, ?z) Λ hasPVComponentWidth(?x, ?b) Λ hasPVComponentLength(?x, ?c) Λ swrlm:eval(?area, "g/z", ?g, ?z) Λ swrlb:equal(?y, ?e) → sqwrl:select(?x, ?z, ?e, ?y, ?g, ?area, ?b, ?c, ?a, ?f) q-8.1

The output from the execution of query q-8.1 in PV-TONS is presented in Figure 8.7.

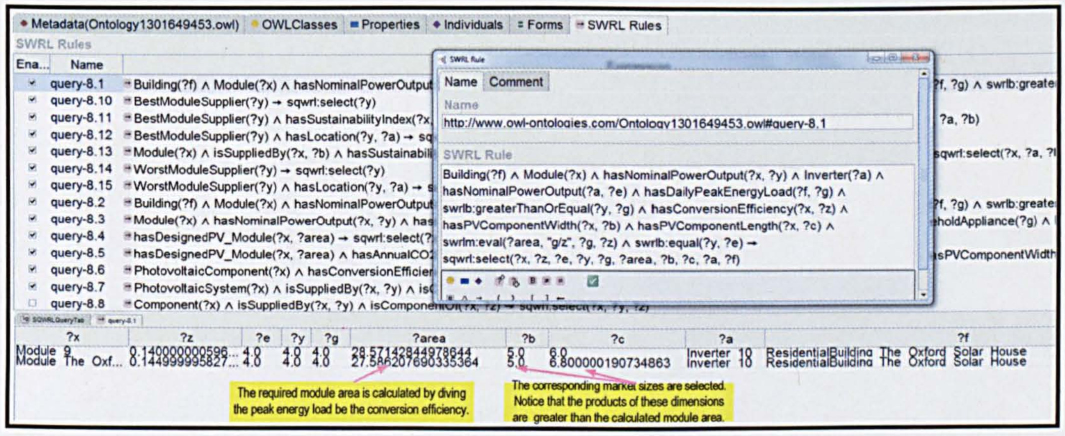

Figure 8.7. Oxford solar house PV-system design using PV-TONS

The nominal power outputs of the different modules in the PV-TONS are compared with the peak daily energy load and only PV-modules with higher values than the peak daily energy load are selected. From the results «Module 9» and «Module The Oxford Solar House» had nominal power output of 4kW equal to the peak daily energy load. These peak daily energy load outputs are divided by the modules' efficiencies (z) to obtain the module area. The calculated module areas are compared with the standard module areas in the knowledge base. The first calculated module area is 27.586m^2. When this is compared with the PV-modules in the knowledge base, two modules with the standard sizes of 34m^2 and 30m^2 are selected. A corresponding inverter with nominal power output equal to the module's peak daily output is selected. The inverter that meets this requirement is «Inverter 10». Given that the nominal power output and the peak daily energy output requirements have been met, the modules and inverter that meet these requirements can now be confirmed as the designed PV-system components. These are «Module 9», «Module The Oxford Solar House» and «Inverter10». The corresponding dimensions of 6.8m x 5m and 6m x 5m are selected. The first dimension corresponds to the designed values obtained for «The Oxford Solar House» according to Roaf *et al.* (2001).

Although the above query yielded the right results, in practice more information is required for making further decisions on the designed PV-system. An example is the sustainability index of the designed PV-system. Query q-8.2 provides a way of determining the sustainability index of the designed PV-module and the results presented in Figure 8.8.

Query 8.2. Design and selection of PV-modules for the Oxford solar house including parameters such as sustainability index

Building(?f) ∧ Module(?x) ∧ hasNominalPowerOutput(?x, ?y) ∧ Inverter(?a) ∧ hasNominalPowerOutput(?a, ?e) ∧ hasDailyPeakEnergyLoad(?f, ?g) ∧ swrlb:greaterThanOrEqual(?y, ?g) ∧ hasConversionEfficiency(?x, ?z) ∧ hasPVComponentWidth(?x, ?b) ∧ hasPVComponentLength(?x, ?c) ∧ hasAnnualCO2Saving(?x, ?h) ∧ hasSustainabilityIndex(?x, ?i) ∧ swrlb:multiply(?d, ?b, ?c) ∧ swrlm:eval(?area, "g/z", ?g, ?z) ∧ swrlb:equal(?y, ?e) →
sqwrl:select(?x, ?h, ?i, ?z, ?e, ?y, ?g, ?area, ?b, ?c, ?d, ?a, ?f) q-8.2

The output from the execution of query q-8.2 in PV-TONS is presented in Figure 8.8.

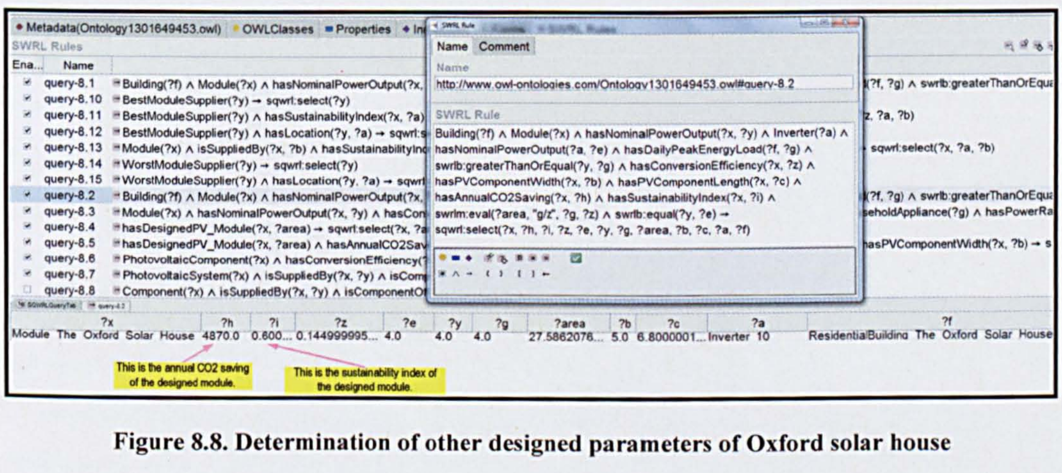

Figure 8.8. Determination of other designed parameters of Oxford solar house

The output of the results in Figure 8.8 is similar to that of Figure 8.7 except that the annual CO_2 savings and sustainability index are also retrieved.

In the previous application, only the peak daily energy load was available for sizing the PV-module. In practice, it is more complexed as there may be need to determine this from the total household appliance ratings. Also, a more generalised approach is used to demonstrate how different PV-systems can be designed. This is examined in the ensuing section.

8.3.2.2 Module design and selection of corresponding PV- system components

This example demonstrates how the total peak daily energy is computed from summing the individual household appliances before using it in the design of PV-systems. In determining the total amount of power used by household appliances, the *hasPowerRating* data-type property is used. The total sum of these power ratings is computed using *sqwrl:makeSet(?s, ?h) Λ sqwrl:sum(?sum, ?s)*. It is important to note that the sizing of module and the inverter depends on this maximum power rating of the household appliances. The sum of all the power ratings of household appliances were determined using the two SWRL functions *sqwrl:makeSet(?s, ?h)* and *sqwrl:sum(?sum, ?s)*. The function defines a container *s* and the sum of the power rating is computed by using *sqwrl:sum(?sum, ?s)* and stored in *s* for later use. The area of the module is computed by using the function *swrlb:divide(?area,?sum,?z)*. This takes into consideration the fact that the total power rating has been captured by the data-type property *hasPowerRating*. Also the inverters' nominal power output has been obtained from Green Book Live database and captured by the data-type property *hasNominalPowerOutput*. The sizing of the PV-system modules using *swrlb:divide(?area,?sum,?z)* yields different sizes of modules found in the PV-TONS system. The challenge is how to select the appropriate module that will provide enough energy to meet the maximum operating power of the building which is conditioned by the power rating of household appliances. Furthermore, how can an inverter be chosen to handle the total maximum power rating of the household appliances. These two challenges were overcome by using *swrlb: equal* and *swrlb:greaterThan* SWRL built-ins. For optimal design, it was opted that the nominal power output of the inverter and the module should be equal and that these nominal power outputs should both be greater than the total power ratings of the household appliances. These were captured with the built-ins *swrlb: equal* and *swrlb:greaterThan*. The combination of the SWRL atoms, SWRL built-ins and SQWRL built-ins has been combined in antecedent of query q-8.3.

Query 8.3. Compact query for PV-module design

Module(?x) ∧ hasNominalPowerOutput(?x, ?y) ∧ hasConversionEfficiency(?x, ?z) ∧ Inverter(?a) ∧ hasNominalPowerOutput(?a, ?e) ∧ HouseholdAppliance(?g) ∧ hasPowerRating(?g, ?h) ˚ sqwrl:makeSet(?s, ?h) ˚ sqwrl:sum(?sum, ?s) ∧ swrlb:equal(?e, ?y) ∧ swrlb:greaterThanOrEqual(?y, ?sum)∧ swrlb:divide(?area, ?sum, ?z) →
sqwrl:select(?x, ?a, ?y, ?e, ?sum, ?area) q-8.3

The execution of query q-8.3 gives the module type, the module size, the inverter type, and the inverter power rating (see Figure 8.9). These results meet the house energy demand of a particular building in which an end-user wants to use a PV-system.

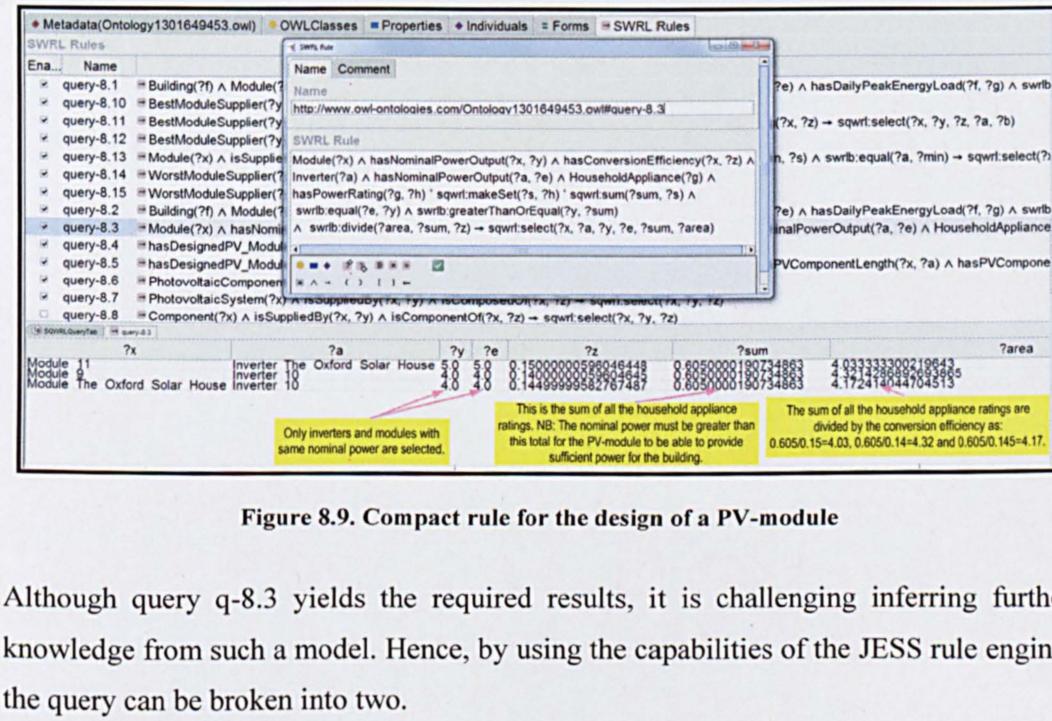

Figure 8.9. Compact rule for the design of a PV-module

Although query q-8.3 yields the required results, it is challenging inferring further knowledge from such a model. Hence, by using the capabilities of the JESS rule engine, the query can be broken into two.

In order to generate the rule, a new data-type property *hasDesignedPV_Module* was created with PV-system component as the ontology domain. The *hasDesignedPV_Module* is modelled as an antecedent of rule r-8.2.

Rule 8.2. Simplified rule for the design of PV-module

Module(?x) Λ hasNominalPowerOutput(?x, ?y) Λ hasConversionEfficiency(?x, ?z) Λ Inverter(?a) Λ hasNominalPowerOutput(?a, ?e) Λ HouseholdAppliance(?g) Λ hasPowerRating(?g, ?h) ˚ sqwrl:makeSet(?s, ?h) ˚ sqwrl:sum(?sum, ?s) Λ swrlb:equal(?e, ?y) Λ swrlb:greaterThanOrEqual(?y, ?sum)Λ swrlb:divide(?area, ?sum, ?z) → hasDesignedPV_Module(?x, ?area) r-8.2

The *hasDesignedPV_Module(?x, ?area)* receives the new knowledge from the JESS engine which is basically module instances and their computed area.

Query 8.4. The selection of the designed PV-module

In order to determine the designed PV-module sizes, a query containing the *hasDesignedPV_Module(?x, ?area)* as the antecedent, and the *sqwrl:select(?x, ?area)* as the consequent is modelled as in query q-8.4.

hasDesignedPV_Module(?x, ?area) → sqwrl:select(?x, ?area) q-8.4

Also the *hasDesignedPV_Module* could be combined with other atoms to generate new knowledge. In query q-8.5, the *hasDesignedPV_Module* is combined with other atoms so as to infer new knowledge about the designed PV-module.

Query 8.5. Inferencing of new knowledge from the designed PV-module

hasDesignedPV_Module(?x, ?area) Λ hasAnnualCO2Saving(?x, ?y) Λ hasSustainabilityIndex(?x, ?z) Λ hasPVComponentLength(?x, ?a) Λ hasPVComponentWidth(?x, ?b) → sqwrl:select(?x, ?z, ?y, ?a, ?b, ?area) q-8.5

The results obtained from the execution of query q-8.5 is presented in Figure 8.10.

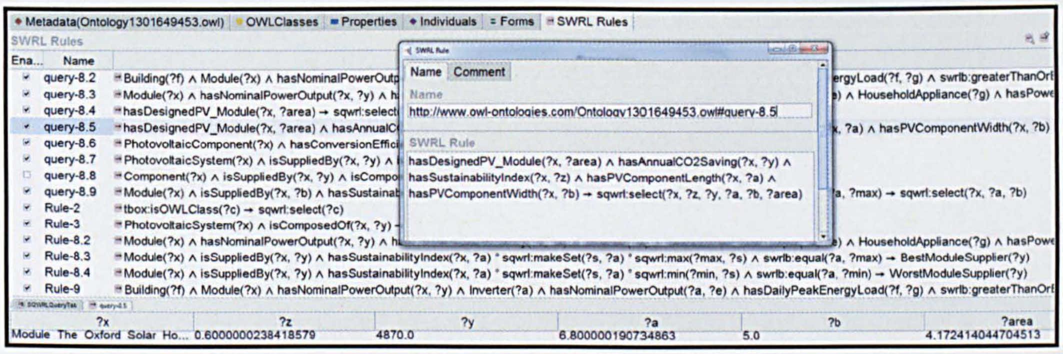

Figure 8.10. Simplified query for the design of a PV-module

So far, the values obtained from PV-TONS from the design of PV-modules have been based on selected PV-module with the nearest surface area. For example, as in Figure 8.7, the computed area of 28.57m^2 of a given module meets the required energy load of 4kW. The PV-module in the market that corresponds to 28.57m^2 is module 9 with the nearest module area of 30m^2. Although a PV-module area of 30m^2 can provide the energy required to meet the building's energy load, in practice, the exact dimensions of the module are required. This dimensional requirement is constrained by the roof size and the fact that market PV-modules do exist in standard dimensions. The space available on the roof may be 6m x 5m. This means a PV-module of 7.5m x 4m may not meet the roof's requirement. Furthermore, the PV-modules available in knowledge base correspond to the standard market sizes different from the computed values. The need to determine the exact dimension that is available in the market and meets the client's requirement is imperative. The next query presented in Figure 8.11 will demonstrate how the exact dimension of a selected PV-module can be determined.

Query 8.6. The determination of the exact dimensions of the PV-modules

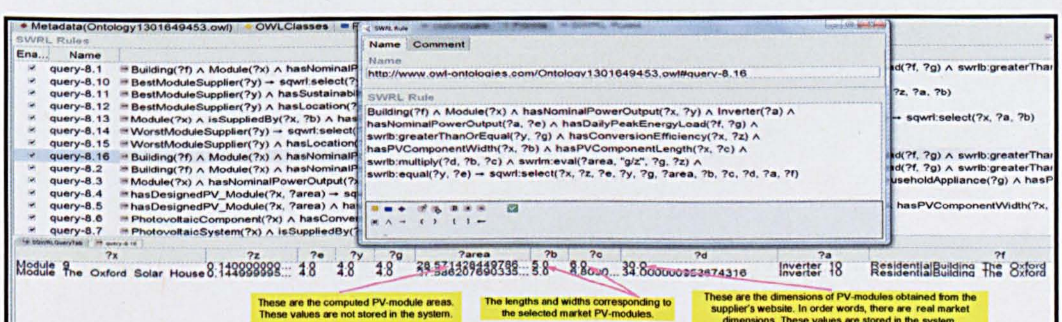

Figure 8.11. The determination of the exact dimenstions of the designed PV-module

The previous section has focused on the design and selection of PV-systems and components. Other than the design and selection of PV-systems and components simple selection decisions can be conducted in PV-TONS. Some examples include the identification of the different conversion efficiencies of PV-moules and the suppliers of the different PV-system components. This is examined in the ensuing sections.

8.3.3 PV-system selection application

8.3.3.1 Simple query for listing PV-systems and efficiencies

Query 8.7. Listing efficiencies of PV-system components

Query q-8.7 demonstrates how the different conversion efficiencies of PV-system components can be retrieved. The query selects PV-system components based on a data-type property.

PhotovoltaicComponent(?x) Λ hasConversionEfficiency(?x,e)
→sqwrl:select(?x,e) q-8.7

This query returns pairs of PhotovoltaicComponent and their structured mode levels. The sqwrl prefix is used to denote SQWRL operators. Implicit in this query is the information that the PhotovoltaicComponent could be any one of its subclasses (ArraySubfield, Array, SubArray, ModulePanel and Module). This semantic querying of an ontological knowledge base makes it possible to obtain information without knowing the detailed syntactic structure of the ontology knowledge base. In other words, semantic queries support the retrieval of both explicit and implicit information based on syntactic and semantic information in the ontology knowledge base (Deokar and El-Gayar, 2009). The output of the results of executing the above query in SWRLTab is shown in Figure 8.12.

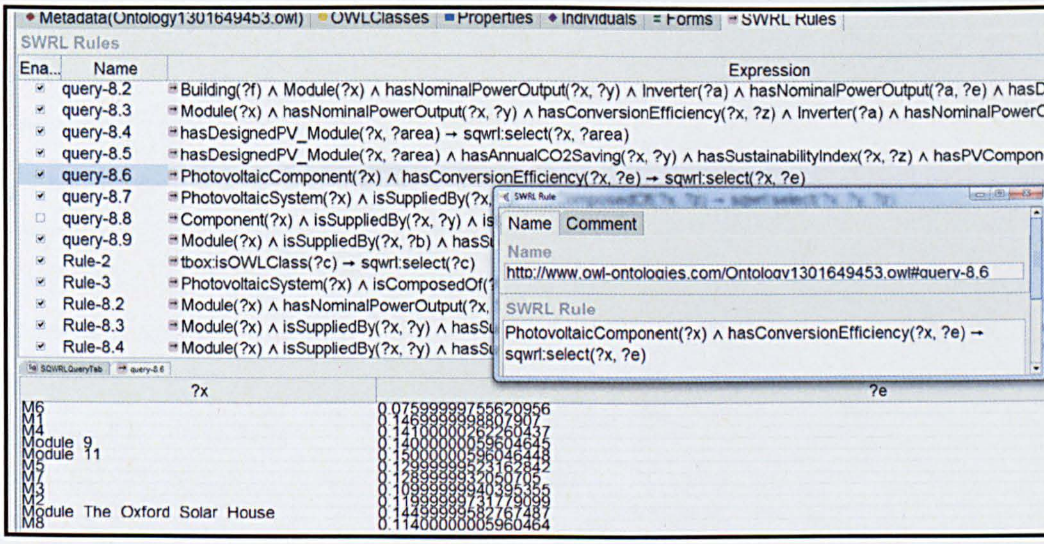

Figure 8.12. Selection of PV-components and their conversion efficiencies

This query exploits the inheritance relationship between the *PhotovoltaicComponent* and its subclasses. In this query all the instances of the subclasses of the *PhotovoltaicComponent* are retrieved. Their corresponding efficiencies are also brought out as output.

8.3.3.2 Finding PV-system supplier

In query q-8.7, the data-type property was used as a criterion in the selection of the different PV-system components. In this section a query that explores composition relationship and object properties will be examined. The query explores the semantic relationships between PV-systems and their suppliers starting from interpreting the PV-system products rather than the suppliers in selecting the different suppliers. For example, the following SWRL antecedent asserts that the combination of *PhotovoltaicSystem*, *isSuppliedBy*, *isComposedOf* atoms implies that the different PV-systems, components and respective suppliers are selected in one goal.

Query 8.8. Compact PV-component selection query

PhotovoltaicSystem(?x) Λ isComposedOf(?x, ?z) Λ isSuppliedBy(?x, ?y) Λ sqwrl:orderBy(?x) → sqwrl:select(?x, ?y, ?z) q-8.8

From the above query, the *PhotovoltaicSystem(?x)* captures the instances of the different types of PV-systems. These components are grid-connected or non-grid-connected. By using the object property *isSuppliedBy(?x,?y),* individual suppliers of the instances of subclasses of the *PhotovoltaicSystem(?x)* are captured. The individual components of these instances are captured through the use of a composition relationship denoted as *isComposedOf(?x, ?z).* An ordering can be placed on the different PV-systems by using the *sqwrl:orderBy* built-in function. The consequent part of the query uses the *sqwrl:select(?x, ?y, ?z)* built-in function to simply retrieve the different PV-systems, their components and their respective suppliers. The advantage in this modelling over traditional databases is that, by using the composition relationship, the different PV-systems instances can be classified according to their different constituents of components.

In determining the suppliers for PV-system using the query above, the suppliers of components were tagged onto the different type of PV-systems i.e. when end-users query for different suppliers, the system reveals the suppliers while at the same time it proposes a combination of the components to form a particular type of PV-system. However, most companies do not provide information about PV-systems in terms of systems (a system here means a combination of components to form a complete functional PV-system); rather they present information about the different components of PV-systems. This is logical and useful in that a wider choice is available to choose the different components and assemble them together to form a complete PV-system. The output of executing query q-8.8 for selecting the different suppliers of PV-system components is presented Figure 8.13.

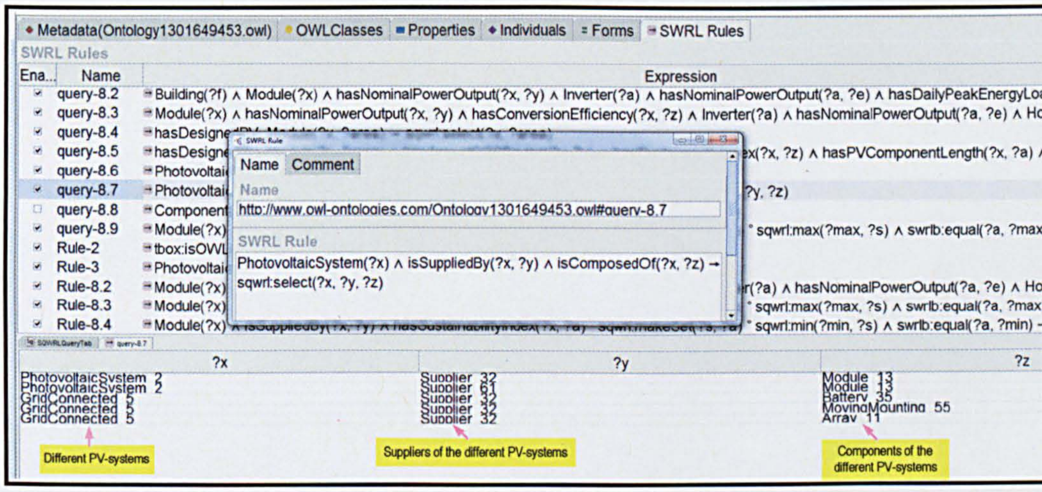

Figure 8.13. Selecting components' suppliers and their PV system components

Figure 8.13 exploits the composition relationship between *PhotovoltaicSystem* and their components. When the query is executed, the instances of *PhotovoltaicSystem* are retrieved. Examples of two of the instances are *GridConnected 5* and *PhotovoltaicSystem 2*. The output is in conformity with how the relation between the class *PhotovoltaicSystem* and *GridConnected System* was defined in Figure 6.8. From Figure 6.8, *GridConnected System* is a type of *PhotovoltaicSystem.* Based on the fact that there is a composition relationship between the class *Component* and the class *PhotovoltaicSystem*, PV-TONS retrieves the corresponding instances of *Component* that constitute a *PhotovoltaicSystem*. An example is a *GridConnected 5* is composed of *Battery 35*. The suppliers of the different instances of PV-system are also retrieved.

Query 8.9. Query for component selection

In query q-8.8, the target was to determine the constituent components of a PV-system and its supplier. The output of the query was the instances of subclasses and their suppliers. Similarly, query q-8.9 is used to select the instances of superclasses instead of subclasses. In this case *isComponentOf*, the inverse of the *isComposedOf* property is used.

Component(?x)Λ isSuppliedBy(?x, ?y) Λ isComponentOf(?x, ?z)→sqwrl:select(?x, ?y, ?z) q-8.9

Query q-8.9 can be used in determining a PV-system if its constituent parts are known. The output of query q-8.9 is presented in Figure 8.14.

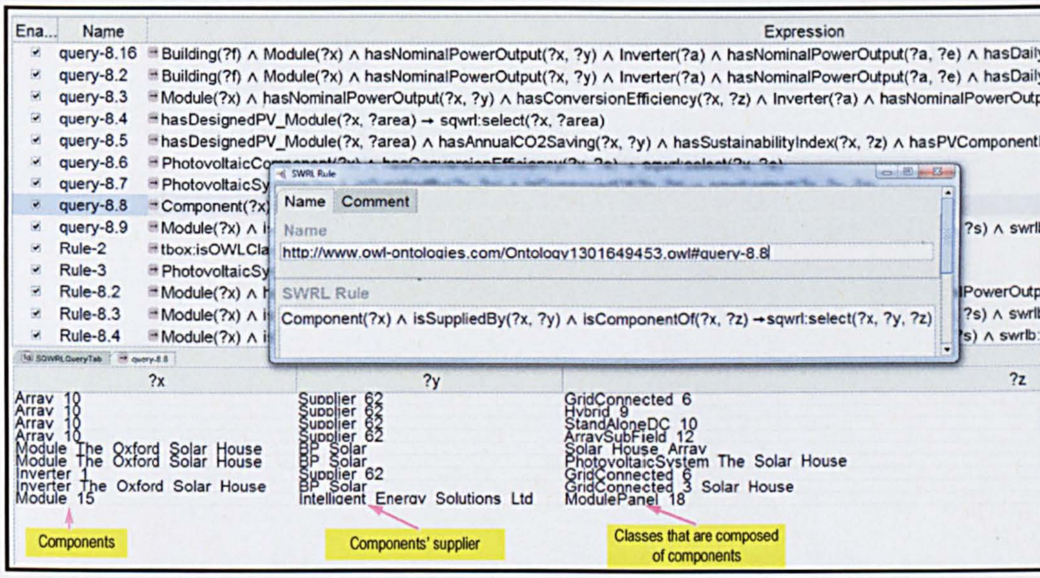

Figure 8.14. Selecting components' suppliers and their PV- system types

From Figure 8.14, the component *Module 15* is a component of *ModulePanel 18*. The different suppliers of components can also be determined.

In the previous example, simple selection queries have been examined. In practice there can be situations where an end-user is not only interested in any type of supplier. He/she may be interested in the best or worst supplier. This requires that the ontology engineer defines what criteria are to be fulfilled by the best or worst suppliers. An example of this practice is in Horridge *et al.* (2007: pp.78), where different instances of the class pizza in the pizza ontology have been partitioned into three subclasses denoting the different spiciness of pizza. The partitions are *Hot, Mild* and *Medium.* A subclass denoted SpicyPizza was created and contained pizzas that have atleast one topping that has spiciness of *Hot*.

Analogically, the sustainability index (*hasStainabilityIndex*) criterion has been used in PV-TONS to establish the best and worst suppliers of PV-systems. The threshold for the criterion has been arbitrarily chosen and can be altered depending on the user's requirement or the quality of the PV-system required. The illustrative queries and rules for determining the best or worst suppliers are examined in the ensuing sections.

8.3.3.3 Finding the best and worst PV- system supplier

In section 8.3.3.2, the SQWRL queries permit users to find the different suppliers of PV-systems. The outcome of one of the queries such as query q-8.9 leaves the end-user with the task of searching through in order to choose the different suppliers. This is not an easy task. Therefore, it is important to incorporate capabilities that can facilitate the process of identifying a type of supplier, e.g. best supplier, worst supplier, supplier with the lowest cost of a PV-system, etc. PV-TONS system has been designed to take care of these challenges. An example is illustrated below with a query that leads to the determination of the best module supplier with respect to the sustainability indices of the different PV-modules.

In determining the different types of suppliers such as the best supplier, constraints or criteria specifying the supplier are explored. This has been examined in the multi-criteria appraisal of the PV-system and its components. In query q-8.10, the best supplier is one with a PV-system of the highest or maximum sustainability index. The following query utilises the values of the data-type property *hasSustainabilityIndex* to determine the sustainability index of each PV-system product. In order to determine the maximum of the sustainability indices, an SQWRL collection built-in *sqwrl:makeSet* is used to transform the sustainability indices into a set. Two SQWRL mathematical operators, *sqwrl:max,* and *sqwrl:equal* are used in determining the maximum sustainability value in the set and ensuring the maximum value is one of the sustainability indices respectively. However, in as much as users may be interested in knowing the sustainability indices they might be interested in knowing the capital cost and the cost saving or other constraints. To capture the capital cost and cost saving, *hasCapitalCost,* and *hasAnnualCostSaving* have been used.

Hence, by combining the following: *hasSustainabilityIndex, sqwrl:makeSet, sqwrl:max, sqwrl:equal*, *hasCapitalCost*, *hasAnnualCostSaving* in the antecedent of query q-8.10 the *sqwrl:select(?x, ?a, ?z, ?y, ?b)* can be used in the consequent in finding the best supplier and the best module.

Query 8.10. Compact rule for the selection of best PV-module and supplier

Module(?x) ∧ isSuppliedBy(?x, ?b) ∧ hasSustainabilityIndex(?x, ?a) ∧
hasAnnualCostSaving(?x, ?y) ∧ hasCapitalCost(?x, ?z) °
sqwrl:makeSet(?s, ?a) ° sqwrl:max(?max, ?s) ∧ swrlb:equal(?a, ?max) →
sqwrl:select(?x, ?a, ?z, ?y, ?b) q-8.10

The output of query q-10 is presented in Figure 8.15.

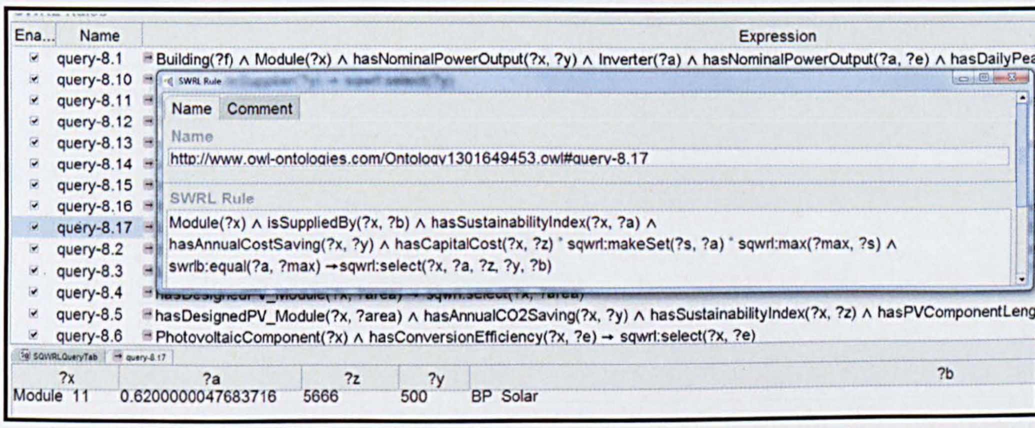

Figure 8.15. Finding the best PV-system and the best supplier

When query q-8.10 is run, the sustainability indices of the different PV-modules are checked. The largest is selected and the corresponding supplier chosen. The capital cost and annual cost saving are also retrieved.

In reality, although modelling queries with the *sqwrl:select* built-in as the antecedent is a compact way of representing SQWRL queries, it has two main disadvantages. Firstly, all necessary requirement characteristics of the module need to be defined right upfront in the precedent part of the query before the antecedent can be executed. Including all the necessary requirements or atoms on the left tends to be too long and the fact that we need to know all these requirements right upfront is a challenge. Secondly ending the query with a built-in makes the query static and cannot be further exploited for other purposes such as inferring new knowledge. For instance, after determining the best PV-system module supplier and the cost saving an end-user may now be interested in finding the location of the supplier.

In order to overcome the limitations posed by modelling as in query q-8.10, the JESS rule engine as explained in Chapter 7 is used. In the first instance, a class is created called the *BestModuleSupplier* to capture instances with the maximum sustainability index. As the *BestModuleSupplier* on its own does not contribute to the PV-system ontology, it is modelled to be a subclass of the general *Thing* concept. Therefore, the rule that determines the best module suppliers is modelled as in rule r-8.3 with the consequent class atom *BestModuleSupplier* replacing the *sqwrl:select* built-in.

Rule 8.3. Classification rule for the selection of best PV-system supplier

Module(?x) Λ isSuppliedBy(?x, ?y) Λ hasSustainabilityIndex(?x, ?a) ˚sqwrl:makeSet(?s, ?a) ˚ sqwrl:max(?max, ?s) Λ swrlb:equal(?a, ?max) →
BestModuleSupplier(?y) r-8.3

Executing rule r-8.3 leads to the selection of best supplier instances. It is important to note that rule r-8.3 is an SWRL rule made up of OWL class and property atoms defined in the PV-TONS system, hence the combination OWL+SWRL. The JESS engine converts a combination of OWL+SWRL into jess facts (i.e. new facts) and the new facts are then sent into the OWL ontology knowledge. These new facts in the OWL ontology can be used to infer new knowledge. For instance, the best module suppliers generated from rule r-8.3 yields some instances that are fed back into the *BestModuleSupplier* class in the PV-TONS. The end-user may be interested in knowing the location of the best supplier and so the new knowledge generated from rule r-8.3 can be combined with the property atom that characterises the location of a supplier. This is modelled as in query q-8.11. Other information about the best supplier can be connected to the *BestModuleSupplier* atom to generate new knowledge about the best module supplier instances captured by the *BestModuleSupplier* without any constraint as would have been the case with query q-8.10.

If an end-user is interested only in the different best suppliers, then query q-8.11 can be executed to extract the new facts that the JESS engine has inserted in the PV-TONS system.

Query 8.11. Simplified rule for the selection of best PV-system supplier

BestModuleSupplier(?y) →sqwrl:select(?y) q-8.11

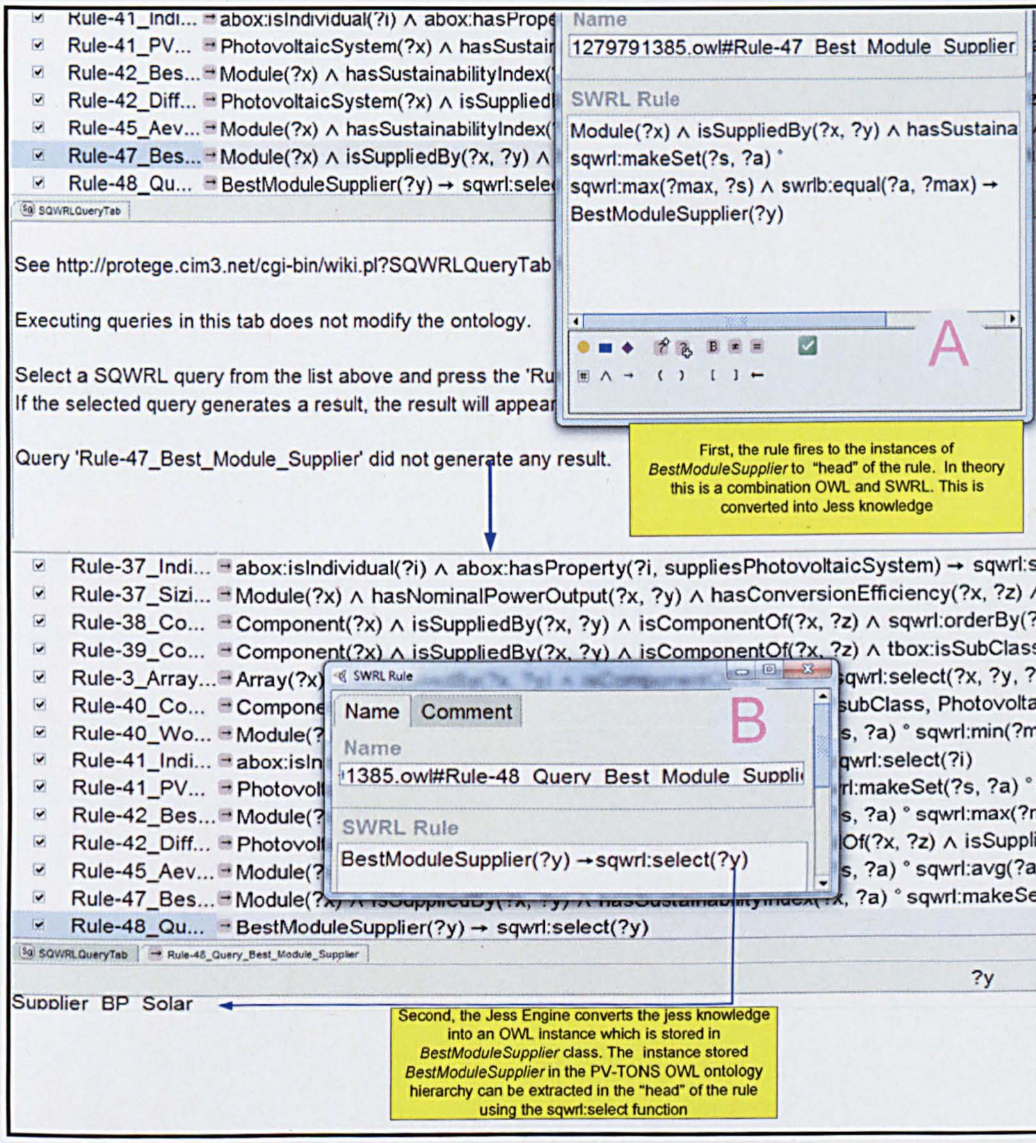

Figure 8.16. Simplified rule for the selection of best PV-system supplier

In **A** the results of executing the body is stored in the head of the rule. In **B**, the stored instances in the body of the rule are fired and the output as shown.

If an end-user decides to buy the PV-system module s/he may want further information about the location of the supplier. By combining the *BestModuleSupplier(?y)* class atom with the data-type property that characterises the suppliers building location, the end-user may obtain more information about the capital cost, annual cost saving and the suppliers' location. This is modelled in query q-8.12.

Query 8.12. Query for the extraction of best PV-system supplier's information

BestModuleSupplier(?y) Λ hasSustainabilityIndex(?x, ?a) Λ hasCapitalCost(?x, ?y) Λ hasAnnualCostSaving(?x, ?z) → sqwrl:select(?x,?y, ?z) q-8.12

By executing query q-8.12, the results in Figure 8.15 are obtained. The main advantage of query q-8.12 stems from the fact that it is actually the head of a rule (i.e. rule r-8.3) that is being re-used. This is a very flexible way of breaking very long rules into short rules and still achieving the same results. Another simple query is the determination of the suppliers' location. This is demonstrated by using query q-8.13.

Query 8.13. Determination of the location of best PV- module supplier

BestModuleSupplier(?y)Λ hasLocation(?y,?a)→sqwrl:select(?y, ?a) q-8.13

The execution of query q-8.13 yields the location of the supplier with the maximum sustainability index, i.e. the best PV-system supplier as earlier defined. This is depicted in Figure 8.17.

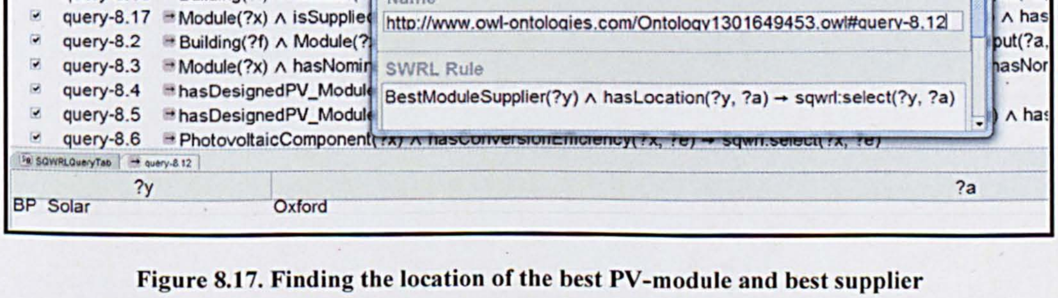

Figure 8.17. Finding the location of the best PV-module and best supplier

Similarly, the rules and queries for specifying the worst module supplier are presented below. It is important to note that while the maximum SWRL built-in function (*sqwrl:max)* has been used in determining the best supplier, the minimum SWRL built-in function (*sqwrl:min)* is used in determining the worst supplier.

Query 8.14. Classification rule for the selection of worst PV-system supplier

Module(?x) ∧ isSuppliedBy(?x, ?b) ∧ hasSustainabilityIndex(?x, ?a) ° sqwrl:makeSet(?s, ?a) ° sqwrl:min(?min, ?s) ∧ swrlb:equal(?a, ?min) → sqwrl:select(?x, ?a, ?b) q-8.14

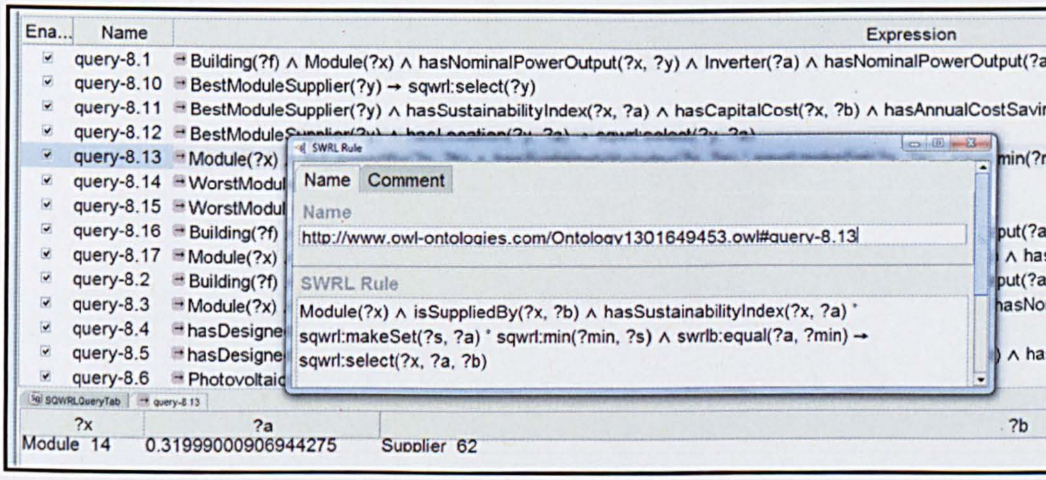

Figure 8.18. Finding the worst PV-system supplier

Rule 8.4. Simplified rule for the selection of worst PV-system supplier

Module(?x) ∧ isSuppliedBy(?x, ?y) ∧ hasSustainabilityIndex(?x, ?a) ° sqwrl:makeSet(?s, ?a) ° sqwrl:min(?min, ?s) ∧ swrlb:equal(?a, ?min) → WorstModuleSupplier(?y) r-8.4

Query 8.15. Simplified query for the selection of worst PV-system supplier

WorstModuleSupplier(?y) → sqwrl:select(?y) q-8.15

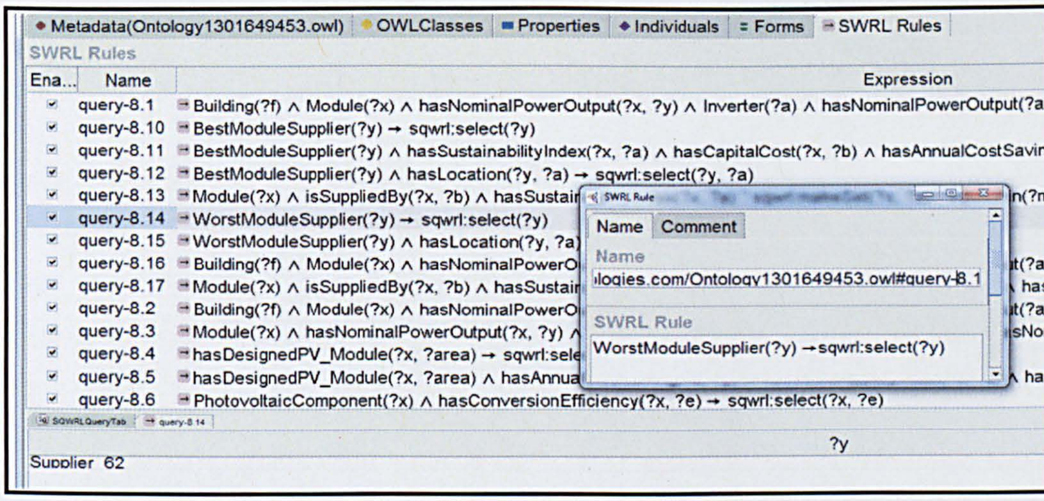

Figure 8.19. Simplified rule for selecting the worst supplier

Query 8.16. Determination of the location of worst PV- module supplier

WorstModuleSupplier(?y) ∧ hasLocation(?y, ?a) →

sqwrl:select(?y, ?a) q-8.16

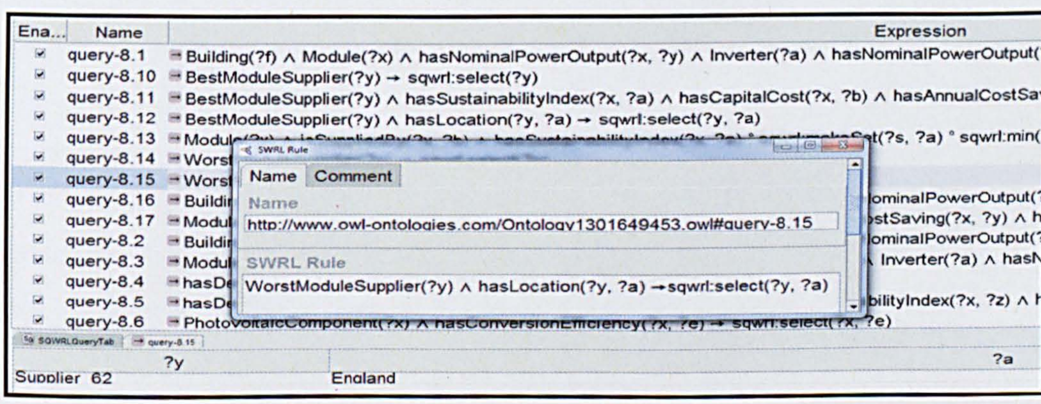

Figure 8.20. Finding the location of the worst supplier

8.4 Conclusion

This chapter discussed the evaluation techniques that were undertaken to verify and validate the reliability of the sustainable building technology and PV-system ontologies. Based on the review of evaluation techniques in Chapter 3, three types appropriate for this study were pursued. The first evaluation techniques entail ensuring that the developed ontologies are semantically correct. In order to achieve this, the aligning/merging technique of semantic verification was used during the development of the ontologies. As ontology development involves so many stages, semantic verification is iterative and is applied to each of the stages whenever errors are discovered. After the semantic verification, syntactic verification was conducted to ensure that the ontologies are free of anomalies. This was undertaken using available reasoners in Protégé-OWL. Like in semantic verification, syntactic verification was conducted at the different stages of ontology development. This was conducted iteratively until all anomalies were eliminated. After the syntactic verification, although not part of the evaluation activity, the language of the ontology was verified to ensure that it was/is compliant to OWL since this was the language used in designing the ontologies. The OWL language compliance was verified using the Manchester OWL language syntax validator.

After the semantic, syntactic and language compliance verification process, a case study with real data was employed in validating the prototype. Some exemplar queries and rules have been executed and presented to demonstrate how some aspects of the semantic web technologies can be used in developing selection and design decision-support systems. The queries and rules in the decision-support system were designed to deal with sizing and the selection of PV-systems and components for the Oxford solar case study. Using the queries it is possible to obtain information about the best and worst PV-system suppliers and the different PV-system available in the market. Above all the PV-TONS can size the different PV-system components given the components characteristics and match the designed sizes of PV-system components to different building requirements such as building energy loads. Although these rules and queries are representative, due to the flexible and extensible nature of ontologies many rules and queries can be created to interrogate PV-TONS.

9. CONCLUSION

9.1 General

The aim of this chapter is to summarize the achievements of the research, the contribution to knowledge, and the scope for further research.

The rationale for this study stemmed from the fact that the mitigation of climate change impacts from all the sectors of the UK economy, including the building sector is becoming significantly important. One of the ways of implementing mitigation strategies is through the sharing of knowledge about sustainable building technologies which can potentially lead to the incorporation in building projects. Unfortunately, one of the most current and widely-used communication technologies, the current web technology has inherent limitations and do not allow the effective and intelligent sharing of information about sustainable building technologies amongst interested users. This condition is further exacerbated by a very large number of different experts working in collaboration on building projects using different vocabulary about sustainable building technology terms. However, semantic web technology, an emerging web technology currently being developed to improve upon the weaknesses of the current web technology, offers great opportunities to be explored. The following main aim was formulated:

"To investigate the extent to which semantic web technologies can be used in developing a decision-support tool for practitioners in making appropriate sustainable building technologies choices for their building projects"

In order to achieve the set aim, the following objectives were formulated:

- To identify, and critically assess the role of sustainable building technologies in the context of sustainability;

- To identify gaps in current web technology in managing sustainable building technology information and exploration of how semantic web technologies can be used in bridging the gaps;

- To elicit, model, and represent sustainable building technology knowledge using semantic web techniques;

- To develop and evaluate a prototype decision-support tool for sustainable building technologies selection in order to demonstrate the potential of semantic web technologies.

9.2 Attainment of the research objectives

The identification and assessment of the role of sustainable building technologies in the context of sustainability in building development

In order to achieve the first objective, a literature review was undertaken on the domain of sustainable building technologies. The review involved an overview of the different applications of sustainable building technologies in construction projects. This was a means to achieve a full understanding of the various emerging sustainable building technologies, their advantages and disadvantages, and the properties that can be used in the characterisation of the sustainable building technologies. The importance of key characteristics such as embodied energy, CO_2 emission, energy efficiency and construction waste in guiding the choice of a sustainable building technology was examined. However, as justified in Chapter 2, a detailed analysis was conducted on PV-system domain. An overview of the challenges to the uptake of sustainable building technologies was conducted. Based on the aim of this study, emphasis was placed on information related challenges. A key aspect highlighted was the way sustainable building technology knowledge was/is being currently managed by the current web. Exemplary websites containing sustainable building technology information were reviewed with some weaknesses idenfified. This served as the starting point for a thorough investigation into the way information is managed in the current web - a task conducted in Chapter 3.

Knowledge gaps in current web technology and exploration of how semantic web technologies can be used in filling the knowledge gaps

The sustainable building technology domain is characterised by too many different definitions, too many synonyms and too much information. It also emerged that the main current information technology, the current web where sustainable building technology is being published, is plagued by so many limitations. Therefore, to explore other media for the publication of sustainable building technology knowledge, it was imperative to examine the weaknesses of the current web technology which is widely used by almost every industry including the construction industry. While chapters 3 and 4 revealed that it is plagued with a number of weaknesses, the current web technology's most important weakness was the fact that it uses HTML, a syntactic language which can only be understood by humans and not machines. As a common example, it was highlighted that if one searches for the word "OWL" from the Google search engine, the output will be pages with information on OWL as a web ontology language and OWL as a bird in the bush. Such a huge amount of information often overwhelms an individual in need of a more specific and relevant information, say OWL for web ontology language. To overcome this weakness, the ontology which is the backbone of the semantic web has gained significant importance in the information science domain. The importance of ontologies and other web technologies has been investigated in this research and used in demonstrating the strength of the semantic web.

The use of the semantic web techniques in eliciting knowledge about the sustainable building technology domain

The fundamental difference in semantic web and the web information is that, information in the current web is syntactic and expressed in HTML; hence it can only be processed by humans. With HTML, web authors tend to embed information using plain English in the HTML syntax. On the other hand, semantic web information is represented using more advanced languages such as RDF and OWL which can easily be processed by both humans and machines. The use of machines means semantic web information can be processed automatically and that web authors can no longer embed information in plain English. The use of semantically rich languages such as RDF and OWL is part of a semantic web vision - i.e. making information machine-processable. To elicit, model and represent building technology knowledge using semantic web techniques, four main activities were pursued. Firstly, a review of the domain of sustainable building technology was undertaken to identify knowledge gaps and existing knowledge models. This led to the exploration of the use of the different semantic web techniques in modelling knowledge about sustainable building technologies. Secondly, based on the review, methodologies often used in the acquisition of knowledge about different domains were identified and used in the acquisition of knowledge in the sustainable building technology domain. For instance, the commonKADS knowledge engineering was used in the acquisition of knowledge; the PROMPT alignment/merging ontology technique was implemented in re-using and semantically verifying existing ontologies and the "Ontology Development 101" methodology was used in the implementation of the conceptual knowledge models developed using CommonKADS and PROMPT. Thirdly, in order to ensure that efficient reasoning can be executed in the knowledge models, it was imperative to use a rich semantic web language. To this end, ontology and semantic web languages were reviewed and the OWL which was further extended to include rules was used. Lastly, it was important to carefully choose advanced semantic web tools that will accommodate the ontology methodology and languages chosen. Thus, Protégé-OWL ontology editor was used in modelling the ontology. In summary, therefore, by using appropriate methodologies, languages and tools, the knowledge about sustainable building technologies and PV-systems were elicited and modelled with rich semantics.

Decision-support tool for the selection of sustainable building technologies

After having elicited, modelled and represented sustainable building technology knowledge using semantic web technologies, it is necessary to implement in a software environment. The sustainable building knowledge model was implemented in Protégé-OWL. To illustrate how different decisions could be made on the use of different sustainable building technologies, the study focused on the PV-system. Consequently, a prototype PV-system technology decision-support system was developed. This was done with the aim of demonstrating the strengths of the semantic web technologies. Based on the data-type properties of the PV-system domain, a multi-criteria technique that provides the options of selecting different technologies, components and suppliers was investigated. Based on the limitations of the multi-criteria method, it was extended to include rules and was implemented in the semantic web environment. Real data from a case study was employed in the prototype. Other sources of data including PV-system information from suppliers' websites were also included. Exemplary queries were undertaken using query and rule languages in extracting information from the prototype. To assess whether the queries produced meaningful answers some query results from the prototype was compared to the results from the case study. This served as a validation of the developed prototype.

In order to achieve the above objectives, a research methodology was designed. Given that both the sustainable building and semantic web technologies are emerging technologies, an exploratory research approach was pursued. First, this led to the assessment of the role sustainable building technologies play in building developments. This led to the achievement of the first objective of this study. Second, identification of knowledge-related challenges in the use of sustainable building technologies and formed the basis of the argument for the need for better knowledge technologies for managing these technologies in building projects. Consequently, a literature review was conducted on the current web and semantic web technologies thereby facilitating clearer understanding of their potential use and challenges in aiding information accessibility and decision-making in building projects. This led to the achievement of the second objective of this study. Based on the review, the two most popular knowledge engineering methodologies - the CommonKADS and "Ontology Development 101" were used in developing sustainable building technology ontology and PV-system knowledge models. This led to the achievement of the third objective of this study. To facilitate reasoning, the OWL and the SWRL languages – both with high expressive power and rich semantics, were included in the knowledge models. Given that the semantic web is an emerging field, a prototype system was developed to demonstrate the strengths of the semantic web. The prototype system was then evaluated through the use of ontology alignment/merging techniques, OWL reasoners and supported by a case study. This led to the achievement of the last objective of this study.

The key findings that emerged from the pursuit of the objectives of this research were identified and are examined in the ensuing sections.

9.3 Key findings from the literature

For clarity the key findings will be examined under the two main themes, i.e. key findings from the review of the sustainable building and semantic web technology domains.

9.3.1 Key findings from the review of sustainable building technology

A literature review has been undertaken to establish the state-of-the-art of sustainable building technologies which led to the following major findings:

The use of different terminologies by different building construction experts

From the review of the sustainable building technology domain, it emerged that many experts are involved in sustainable building projects. Their disciplines of expertise greatly vary and include surveying, mathematics, environmental engineering, computer science, construction IT, etc. The usage of particular terminologies differs between experts. No rules exist for facilitating the understanding of different terminologies. Common word problems, such as the use of the same term for different meanings by different experts or vice versa exist. All these reasons highlighted the need for the creation of a unified, complete and consistent terminology for use by different practitioners working in collaboration on building projects.

The availability of too much emerging knowledge about the sustainable building technology domain

Based on the review of the literature, it emerged that manufacturers, government agencies, construction professionals and researchers are publishing enormous amount of information over the web about the sustainable building technologies. The existence of a huge amount of emerging knowledge about sustainable building technologies was established as one of the reasons rendering the knowledge elicitation process complex and tedious, hence overwhelming clients who often require knowledge about sustainable building technologies. Furthermore, some of the information is published using different formats which further exacerbate the difficulty in the elicitation process of knowledge about sustainable building technologies from different sources.

The existence of discrepancies in the definition of sustainable building technology terminologies

Based on the literature review, many terminologies were defined differently. For instance there are at least 200 different definitions of sustainable development. The most striking case is the definition of *modern methods of construction.* POSTnote (2003), Burwood and Jess (2005), Energy Saving Trust (EST, 2005), Barker 33 Cross industry Group (Barker 33, 2006) and ODPM (2005) have all defined modern methods of construction differently.

The identification of key sustainable building technologies' properties for characterising the environmental performance of building

The review of sustainable building technologies applied to building development projects (examining current practices i.e. methods of construction, materials, building technologies and stakeholders' involvement) led to the establishment and identification of key sustainable building technologies' properties that can be used in quantifying the environmental performance of a building. Furthermore, the properties of the different sustainable building technologies can be used in making informed decisions about their uses in different building development projects. For example, the incorporation of PV-system technology into buildings can significantly reduce CO_2 emissions, compared to if conventional grid-electricity is used.

Reluctance in the uptake of sustainable building technologies despite government's support

It emerged from the literature that, although the government has been advocating the use of sustainable building technologies, its uptake has been very slow (Egan 1998; POSTnote 2003). This has partly been due to lack of (a) knowledge about sustainable building technologies and (b) the best way to disseminate the knowledge (Shelbourn *et al.*, 2006).

The availability of other existing knowledge models for use in the sustainable building technology domain

Based on the literature review, no other knowledge models were found appropriate for use in modelling sustainable building technology knowledge. However, IFC - a semantic and Uniclass - a knowledge taxonomy were noted as being the most widely used in the construction industry for information exchange. IFC and Uniclass were not suitable for direct use as they existed only in text books. Nonetheless, in re-using these knowledge models, they had to be manually edited using appropriate ontology tools.

Similarities and dissimilarities amongst the different sustainable building technologies

From the literature review, it emerged that most sustainable building technologies share common characteristics. Some common characteristics shared by these technologies are energy efficiency, CO_2 emission levels and waste generation, etc. Most of the common characteristics were used as data-type properties which served as criteria in distinguishing between the different technologies. In as much as there are common characteristics amongst the different sustainable building technologies, there are significant differences among the different technologies. For example, the design and selection approach of combined heat and power is different from the design and selection approach of PV-systems. In knowledge-based systems the similarities and differences of characteristics are often represented at the generic and specific levels through the exploitation of inheritance relationship. This was considered in the design of sustainable building tyechnology ontology.

9.3.2 Key findings from the review of semantic web technology

The review of semantic web technology literature led to the following findings:

Lack of sustainable building technology ontology

An examination of previous semantic web technology applications to construction projects reveals that: (a) most ontologies in construction are generic in nature addressing top level concepts (Lima *et al.,* 2003), (b) most semantic web technologies have been explored in annotating building specifications and drawings (van Rees and Tolman, 2004), (c) some semantic web technologies have been explored in project management (Ruikar *et al.*, 2007) with none on sustainable building technology. In summary most semantic web applications are prototypes for demonstration and exploratory purposes.

Limitations of the current web technology

An investigation of the current use of web technology by construction companies reveals that although it has been successful there are still some challenges to over come. These challenges are: (a) the current web's limitations in the processing of information (Ruikar *et al.*, 2007), (b) the complexity of construction projects and (c) the fragmentation of the UK construction industry (Udeaja, 2002). These limitations have rendered construction knowledge complex for both human and machine processing.

Lack of common standards in representing construction information

A review on current knowledge management reveals that most companies write their databases in their own format and tend to pay less attention on improving an efficient knowledge management techniques such as the semantic web technology. Most are not aware of the benefits that could be accrued from implementing more efficient knowledge management techniques (Olugbode *et al.*, 2008).

The use of semantic web in other industries

It also emerged from the literature that research in semantic web technologies is gaining ground in other industries such as the telecommunications and medicines. Although the researches are still in their infancy stages, the results so far demonstrate the strength of semantic web technologies in rendering information understandable both by machines and humans.

Existence of frameworks for building the semantic web

Frameworks for building semantic web such as Jena, Visual studio and Protégé-OWL API were reviewed. It was found that most of these semantic web development toolkits were/are still under active development and most are still not yet stable from a software engineering point of view. However, Jena and Protégé-OWL API, being open source are widely popular and commonly used in the academia.

Limitation and the evolutionary nature of the web languages

A review of ontology languages revealed that since the emergence of the semantic web, these languages have been growing in number and in strength or efficiency in reasoning. Common ontologies languages in order of increasing efficiency reviewed are the XML, RDF, RDFS and OWL. Based on this review, each of the ontology languages had limitations and proceeding languages being built to improve the preceding ones. OWL has been chosen as it overcomes the limitations of the preceding languages (i.e. it provides sufficient expressiveness to provide the ontology descriptions required to support the semantic web).

Disparity in the different ontology engineering methodologies

Many ontology development methodologies were reviewed with a focus on the following: "Ontology Development 101" (Noy and McGuinness, 2001), Methontology (Fernández-López *et al.,* 1997) and the Toronto Virtual Enterprise project methodology (Grüninger and Fox, 1995). It was found that some methodologies addressed ontology development from scratch while others addressed them from using existing ontologies and that the suitability of each methodology depends on the purpose of the ontology. It was also found that very few tools support ontology engineering methodologies. A key factor considered in this study was to choose a methodology that is supported by an ontology editing tool. To this effect, "Ontology Development 101" was chosen. As well as being the most popular it is supported by Protégé-OWL editor.

Disparity in the different knowledge engineering methodologies

A number of knowledge engineering methodologies have been reviewed including CommonKADS (Schreiber *et al.*, 2000), MOKA (Stokes, 2001), 47 Step-procedure (Milton, 2007) and Top-down Object-based Goal-oriented Approach (TOGA) (Gadomski, 2008), methodologies. Based on a detailed analysis of these methodologies, it emerged that CommonKADS is more mature and has been widely acknowledge as the leading *de facto* standard for knowledge analysis and knowledge intensive system development in Europe (Schreiber *et al.*, 2000).

Disparity in the different ontology editing tools

A review of most ontology editors revealed that most of them depended directly on ontology languages and methodologies and this is reflected in the ease or difficulty in developing a given ontology. Given that OWL has been chosen as the ontology language in this study, suitable and compatible ontology editors are required. Accordingly, the following editors were reviewed: KAON (Maedche *et al.*, 2003), OilEd (Bechhofer *et al.*, 2001), Ontolingua Server (Farquhar *et al.*, 1997), OntoSaurus (Swartout *et al.,* 1997), WebODE (Arpirez *et al.*, 2003), WebOnto (Dominigue, 1998) and Protégé-OWL. After a critical comparison, Protégé-OWL emerged as the best in terms of ease of use, popularity, support for ontology libraries, compatibility with useful plug-ins and the OWL language.

The limitation on the different web browsers for the presentation of ontologies

With the interest in the semantic web growing at a very high rate from researchers with different backgrounds and with limited or no experience in the semantic web, the need to develop user interfaces for ontology navigation is imperative. There are already studies towards developing web browsers for ontology browsing. However, those that currently exist in the literature are still very lightweight ontology browsers. Some examples are OWLSight, Protégé-web browser, and OWL ontology-browser already examined in Chapter 3.

9.4 Contribution to knowledge

In the process of investigating how to attain the aim and objectives of this study, the following achievements which have significantly contributed to knowledge in both the area of sustainable building and semantic web technology were made. The contribution to knowledge could be classified into four main groups: theoretical, methodological, practical and from an application point of view.

9.4.1 Theoretical contribution

The main contribution in the development of conceptual knowledge models of sustainable building technology

The main achievement in this section is the development of conceptual knowledge models of the sustainable building technology domain that can be exploited for further use. The development of conceptual knowledge models stemmed from the fact that current knowledge models about the domain of sustainable building technology suffer from two major setbacks. First, sustainable building technology knowledge components exist as disparate models with no relationship between them. For instance, in the literature, modern method of construction is often considered as a separate domain and hardly considered alongside the widely known renewable technology as sustainable building technologies. In reality, these two domains share some common properties. These technologies are energy efficient technologies and can be related through the property of energy efficiency. Second, the current web treats sustainable building technology knowledge concepts as if they were different. For instance, green building will yield results different from those of sustainable building. Conceptual knowledge modelling constitutes the first step in specification of concepts such that there can be a common agreement in the definition of a concept using different terminologies. Conceptual knowledge models can be used as the basis for the development of ontologies.

The main contribution in the development of the conceptual knowledge model for the PV-system

Cognizance of the huge nature of the domain of sustainable building technology, the PV-system domain was chosen as a particular case to demonstrate the semantic web capabilities. Although the PV-system concept has been captured at a higher knowledge level in sustainable building technology domain, it was necessary to break-down the PV-system higher knowledge level into sub-concepts to allow rich semantics to be captured for use in intelligent and automatic inferencing. Hence, a PV-system conceptual model was developed. A major benefit of the the PV-system conceptual model is that it can be used in the development of other applications such as in developing ontologies.

The main contribution in the development of the PV-system ontology

The PV-system ontology developed in this study models knowledge about the PV-system technology. Depending on the type of application, the PV-system technology ontology can be used in other semantic web applications.

9.4.2 Methodological contribution to knowledge

The main contribution in the establishment of a semantic web approach for the management of sustainable building technology knowledge

The main achievement in this area is the establishment of a semantic web approach that enables knowledge in the sustainable building technology domain and the PV-system technology domain to be represented and interpreted by computers for decision-support purposes. A key approach is the use of PROMPT alignment/merging technique in semantically verifying textual information abstracted from the literature.

The main contribution in the extension of the multi-criteria decision techniques to include semantic web rules

In this study, a multi-criteria technique was developed and used in the selection of different PV-systems. The limitations of the multi-criteria techniques led to the need for the transformation of the multi-criteria matrix to a rule format for developing an ontology knowledge-based system. In conducting the transformation, the assessment criteria of sustainable building technologies and PV-systems in the multi-criteria matrix were modelled as ontology properties in the ontology knowledge-based system. Furthermore, to facilitate reasoning, OWL constraints and SWRL restrictions were included. SWRL rules and SQWRL queries that can be used in reasoning and querying were included. Thus, the multi-criteria system has been included as an integral sub-component of the ontology knowledge base. This is an innovative technique that extends multi-criteria system to include rules that facilitate efficient reasoning.

9.4.3 Practical contribution to knowledge

The main contribution in the development of PV-system decision-support system (i.e. the PV-TONS)

The main contribution in this section is the development of a prototype system for PV-system decision-support demonstrating the potential of semantic web technology.

9.4.4 Contribution to knowledge from an application point of view

The main contribution in the technical design of PV-system

From an application point of view, the main contribution is the use of the PV-TONS system for designing PV-systems using the semantic web approach. The PV-TONS system provides a means of designing PV-systems and components. It further provides ways of making alternative choices in the selection of PV-systems and their suppliers in an automatic fashion.

9.4.5 Contribution in terms of publication output

During the course of this study, knowledge was gained from three main fields. These are general research skills, an in-depth knowledge about both the domain of sustainable building technologies and semantic web technologies. The skills and knowledge gained were used in writing and publishing: four peer-reviewed journal papers, a book chapter, a funded research report, and ten peer-reviewed conference papers. Furthermore, in addition to the four published journal articles a fifth article and the most important of all about a PV-TONS prototype, the key product of this study has been submitted to the journal of Information Sciences. A list of these publications is presented in appendix 9.1.

9.5 Challenges and limitations of the research

9.5.1 Challenges

In conducting this research two main challenges were encountered. This study was constrained by the evolving nature of the semantic web technology. Many emerging semantic web technologies are currently under-development with some of the semantic web software still very unstable. For instance, although Protégé-OWL editor is the most widely used semantic web tool, it still contains bugs and is still undergoing development. This was a challenge as it hindered the full exploration of the semantic web technologies. Furthermore, it was difficult to identify some of the bugs and as a result, it was equally difficult to establish whether the inability of the semantic web tools to undertake a given task was due to the tool's weaknesses or the presence of bugs.

The second challenge is based on emerging nature of the semantic web. Given that the semantic web technology is still emerging, learning resources were/are very limited. For example, unlike in most computer science fields where video tutorials are freely available online, there are very limited number of semantic web tutorial videos online for use by learners. Also, the diversified nature of the different branches of the semantic web poses serious challenges in terms of how quickly one can easily learn the technology. These are challenges that steepen the learning curve of semantic web technologies and can potentially be a set-back to individuals interested in semantic technololgies and applications especially non-computer literates.

9.5.2 Limitations of the research

In this study, a PV-system prototypical ontology knowledge base has been developed to enhance knowledge sharing and re-use about the PV-system domain. The rationale for an ontology knowledge-based system was to explore the strengths of the semantic web and thus overcome the limitations of the current web technologies. Nonetheless, in the development of the prototype, the following limitations were uncovered:

- Given the nascent nature of the semantic web technology domain, most of its constituent technologies are still very limited in scope. This limits the exploitation of the full potentials of the semantic web. For instance, the SWRL built-ins for computation are limited to a very small set of mathematical operations. That is why the sustainability index of PV-systems was manually calculated before being input into PV-TONS. There is a scope to further investigate better ways of handling complex mathematical equations in the semantic web;

- Based on the review of the literature on sustainable building technologies, two key facts emerged. Firstly, there are similarities in most sustainable building technologies. For instance, the fact that some of the technologies are energy efficient, sustainable and carbon neutral. Secondly, in as much as these similarities exist, there exist major differences as well. For example, the method of design and selection of combined heat and power is totally different from the design and selection of PV-systems. This means that, within the time frame of this research it was not possible to tackle all the different sustainable building technologies. The focus was on PV-systems leaving a scope to further investigate the application of semantic web technologies on the different sustainable building technologies;

- In the case study application for the design of PV-systems, only the design of PV-modules and inverters were considered. In practice other PV-system components including the batteries, cables and generators are normally designed. However, because of the complex computational relationship between these components and the fact that SWRL built-ins are limited in handling complex computational operations, they were not considered. There is scope to investigate how best the design of the whole PV-system components can be conducted;

- PV-TONS is a stand-alone ontology knowledge-based system and access is not provided to extract information about PV-systems from other information systems. Hence, the effort and time required to manually populate PV-TONS with PV-system instances and associated property information is very challenging. With regards to this, there is scope for automating the exchange of PV instances data between PV-TONS and other databases including the current web system.

9.6 Recommendations for further research

A PhD research, due to its scale of work and time constraints, invariably discovers new issues that need to be further investigated to advance the subject area. In addition to using semantic web techniques in modelling complex knowledge about the sustainable building technology domain, the work described in this thesis has generated and highlighted research areas that require further attention. These areas have been grouped into five categories i.e. the expansion on scope of domain of application, the automation of the ontology comparison process, the development of a central database, the development of user interfaces and the need to connect to the web.

Expand on scope of domain of application

In this study, a review was conducted on the different types of sustainable building technologies. Some major sustainable building technologies include solar, wind turbines, hydro, combined heat and power, tidal, and geothermal technologies. Although it was established that these technologies have some common characteristics such as being energy efficient, renewable, clean, and have low impacts on the environment, it also emerged that there is a great knowledge-level disparity between these technologies. For instance, their design and selection methodologies are different. This difference is partly attributed to the different criteria that need to be considered in the design methodology. For example, combined heat and power is more appropriate in district or community settings than a PV-system. This means that while the design of combined heat and power may consider urban data such as the community population and building density (number of buildings per unit area), the design of the PV-system may simply use household data. Thus, different computation approaches are required. Considering that this study focused on the PV-systems, it means that the design and selection of PV-systems are not applicable to other sustainable building technologies. However, given that sustainable building technology ontology has been developed in this study, it can serve as a starting point for further exploration of the applications of semantic web to other sustainable building technologies. This direction is worth investigating especially given the fact that the implementation of some of these technologies in practical settings does have influences on other existing technologies.

Automation of the ontotology comparison process

In this study, the PV-system ontology was semantically validated manually using the PROMPT alignment/merging technique. Although this led to the desired results, the process was very tedious and time consuming. The comparison process of different ontologies could be improved by using automated techniques. As part of future research, it will be important to investigate better automated techniques in comparing knowledge models about the domain of sustainable building technology. This is particularly important as more and more knowledge taxonomies about sustainable building technologies are being uploaded onto the web at an alarming rate.

Development of a central database

In this study, the share size of information about sustainable building technologies meant that the need to focus on a particular area was imperative. To this effect, from a holistic point of view a generic ontology about the sustainable building technology was developed to provide an overview of this domain. As explained in Chapter 1, an application ontology about PV-system ontology was also developed. These two ontologies reveal complex interrelationships between the ontological concepts in both the domain of sustainable building technology and the PV-system. This means increasing the scope for further studies to include other sustainable building technologies will further exacerbate the complexity of the interrelationships between ontological concepts. Although, a file system was used for storing the ontologies in this study, there is need to investigate other database management systems that will cope with the huge amount of complex interrelationships in the sustainable building technology ontology should the current ontology be extended to include other sustainable building technologies. As explained in Chapter 7, using a database management system can significantly improve flexibility, extensibility, scalability and re-usability.

Development of user interfaces

In this study, sustainable building technology and PV-system ontology knowledge-based systems have been developed to enhance knowledge sharing and re-use. The rationale for an ontology knowledge-based system was to explore the strengths of the semantic web and thus open research areas to improve upon the current web technologies. This exploratory study culminated into the design of a semantic web prototype system that contained sustainable building technology knowledge. Although the prototype system exists as a back-end technology, an easy-to-use interface of Protégé-OWL plug-ins (e.g. SWRLTab) was used to enhance accessibility of knowledge from the system. However, given the dependence of this interface on Protégé-OWL, it is challenging to end-users with limited or no skills in OWL-related plug-ins technologies. Hence, there is need to develop user-friendly interfaces independent of OWL technologies that can facilitate the acquisition of knowledge from the prototype system. This will be considered as part of future research.

Connecting to the web

The fundamental problem highlighted in this study is the inability of the current web to contain the increasing amount of information about most emerging technologies including the sustainable building technologies. This sheer increase in the amount of information about different technologies being uploaded onto the web is driven by the sheer number of users browsing the web. Recent estimates by the United Nations put the number of internet users to exceed 2 billion (nearly a third of the world's population) in 2010 (BBC, 2010). This sheer increase in the number of web users can be attributed to the growing interest in promoting business supported by the current web as this is faster, cheaper, more personalised and at the moment the best medium for information exchange. Thus, it is believed that online transactions have the potential to radically transform the way businesses and construction project management operations are conducted between project organisations or practitioners. The involvement of many stakeholders including government agencies, businesses, researchers and construction professionals in sustainable building technologies means the use of an efficient web technology has the potential to radically spur the incorporation of sustainable building technologies into different projects. However, in this study, the sustainable building technology framework has been implemented in local or Personnal Computer (PC)-based prototype. Further studies should inquire implementing the framework in a web-based application using emerging web paradigms including the N-tier layer system proposed in Chapter 7.

Finally, there are other application areas that have been suggested in this study such as the investigation of the integration of multi-criteria decision techniques applied to sustainable building technologies with ontologies and rules. The achievement of these research goals can significantly improve the efficient, effective collaboration and knowledge sharing about sustainable building technologies in the building sector. From the key findings of this study, there is no doubt the semantic web technologies can significantly contribute in enhancing effective collaboration and knowledge sharing between project partners. This can potentially raise the level of awareness, facilitate capacity building, and build confidence (which is missing today) of interested stakeholders in the uptake of sustainable building technologies. The benefits to individuals and the society both present and the future are quite considerable and cannot be over-emphasized.

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APPENDICES

Appendix 7.1. PV-TONS system OWL ontology


```
<?xml version="1.0"?>


<!DOCTYPE rdf:RDF [
 <!ENTITY owl "http://www.w3.org/2002/07/owl#" >
 <!ENTITY swrl "http://www.w3.org/2003/11/swrl#" >
 <!ENTITY swrlb "http://www.w3.org/2003/11/swrlb#" >
 <!ENTITY xsd "http://www.w3.org/2001/XMLSchema#" >
 <!ENTITY rdfs "http://www.w3.org/2000/01/rdf-schema#" >
 <!ENTITY rdf "http://www.w3.org/1999/02/22-rdf-syntax-ns#" >
 <!ENTITY protege "http://protege.stanford.edu/plugins/owl/protege#" >
 <!ENTITY xsp "http://www.owl-ontologies.com/2005/08/07/xsp.owl#" >
 <!ENTITY swrla "http://swrl.stanford.edu/ontologies/3.3/swrla.owl#" >
 <!ENTITY tbox "http://swrl.stanford.edu/ontologies/built-ins/3.3/tbox.owl#" >
 <!ENTITY abox "http://swrl.stanford.edu/ontologies/built-ins/3.3/abox.owl#" >
 <!ENTITY swrlm "http://swrl.stanford.edu/ontologies/built-ins/3.4/swrlm.owl#" >
 <!ENTITY sqwrl "http://sqwrl.stanford.edu/ontologies/built-ins/3.4/sqwrl.owl#" >
]>


<rdf:RDF xmlns="http://www.owl-ontologies.com/Ontology1301649453.owl#"
 xml:base="http://www.owl-ontologies.com/Ontology1301649453.owl"
 xmlns:protege="http://protege.stanford.edu/plugins/owl/protege#"
 xmlns:xsp="http://www.owl-ontologies.com/2005/08/07/xsp.owl#"
 xmlns:abox="http://swrl.stanford.edu/ontologies/built-ins/3.3/abox.owl#"
 xmlns:sqwrl="http://sqwrl.stanford.edu/ontologies/built-ins/3.4/sqwrl.owl#"
 xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
 xmlns:swrl="http://www.w3.org/2003/11/swrl#"
 xmlns:swrlm="http://swrl.stanford.edu/ontologies/built-ins/3.4/swrlm.owl#"
 xmlns:owl="http://www.w3.org/2002/07/owl#"
 xmlns:xsd="http://www.w3.org/2001/XMLSchema#"
 xmlns:swrlb="http://www.w3.org/2003/11/swrlb#"
 xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
 xmlns:tbox="http://swrl.stanford.edu/ontologies/built-ins/3.3/tbox.owl#"
 xmlns:swrla="http://swrl.stanford.edu/ontologies/3.3/swrla.owl#">
 <owl:Ontology rdf:about="">
  <owl:imports rdf:resource="http://swrl.stanford.edu/ontologies/built-ins/3.3/abox.owl"/>
  <owl:imports rdf:resource="http://sqwrl.stanford.edu/ontologies/built-ins/3.4/sqwrl.owl"/>
  <owl:imports rdf:resource="http://swrl.stanford.edu/ontologies/built-ins/3.4/swrlm.owl"/>
  <owl:imports rdf:resource="http://swrl.stanford.edu/ontologies/3.3/swrla.owl"/>
  <owl:imports rdf:resource="http://swrl.stanford.edu/ontologies/built-ins/3.3/tbox.owl"/>
 </owl:Ontology>
 <owl:AllDifferent>
  <owl:distinctMembers rdf:parseType="Collection">
   <rdf:Description rdf:about="#Module_The_Oxford_Solar_House"/>
   <rdf:Description rdf:about="#M1"/>
   <rdf:Description rdf:about="#M2"/>
   <rdf:Description rdf:about="#M3"/>
   <rdf:Description rdf:about="#M4"/>
   <rdf:Description rdf:about="#M5"/>
   <rdf:Description rdf:about="#M6"/>
   <rdf:Description rdf:about="#M7"/>
   <rdf:Description rdf:about="#M8"/>
  </owl:distinctMembers>
```

```
</owl:AllDifferent>
<owl:AllDifferent>
 <owl:distinctMembers rdf:parseType="Collection">
  <rdf:Description rdf:about="#GridConnected_3_Solar_House"/>
  <rdf:Description rdf:about="#GridConnected_5"/>
  <rdf:Description rdf:about="#GridConnected_3"/>
  <rdf:Description rdf:about="#GridConnected_6"/>
 </owl:distinctMembers>
</owl:AllDifferent>
<owl:AllDifferent>
 <owl:distinctMembers rdf:parseType="Collection">
  <rdf:Description rdf:about="#Inverter_The_Oxford_Solar_House"/>
  <rdf:Description rdf:about="#Inverter_10"/>
  <rdf:Description rdf:about="#Inverter_7"/>
  <rdf:Description rdf:about="#Inverter_1"/>
 </owl:distinctMembers>
</owl:AllDifferent>
<owl:AllDifferent>
 <owl:distinctMembers rdf:parseType="Collection">
  <rdf:Description rdf:about="#ModulePanel_18"/>
 </owl:distinctMembers>
</owl:AllDifferent>
<owl:AllDifferent>
 <owl:distinctMembers rdf:parseType="Collection">
  <rdf:Description rdf:about="#Intelligent_Energy_Solutions_Ltd"/>
  <rdf:Description rdf:about="#Company_1"/>
  <rdf:Description rdf:about="#Company_2"/>
  <rdf:Description rdf:about="#Company_3"/>
  <rdf:Description rdf:about="#Company_4"/>
 </owl:distinctMembers>
</owl:AllDifferent>
<owl:AllDifferent>
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  <rdf:Description rdf:about="#Company_1"/>
  <rdf:Description rdf:about="#Intelligent_Energy_Solutions_Ltd"/>
  <rdf:Description rdf:about="#Company_2"/>
  <rdf:Description rdf:about="#Company_3"/>
  <rdf:Description rdf:about="#Company_4"/>
  <rdf:Description rdf:about="#BP_Solar"/>
  <rdf:Description rdf:about="#Supplier_62"/>
  <rdf:Description rdf:about="#Supplier_61"/>
  <rdf:Description rdf:about="#Supplier_32"/>
 </owl:distinctMembers>
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  <rdf:Description rdf:about="#ArraySubField_12"/>
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</owl:AllDifferent>
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  <rdf:Description rdf:about="#MovingMounting_55"/>
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  <rdf:Description rdf:about="#M1"/>
  <rdf:Description rdf:about="#M2"/>
  <rdf:Description rdf:about="#M3"/>
```

```
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<rdf:Description rdf:about="#M5"/>
<rdf:Description rdf:about="#M6"/>
<rdf:Description rdf:about="#M7"/>
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<rdf:Description rdf:about="#M3"/>
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<rdf:Description rdf:about="#Inverter_10"/>
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</owl:AllDifferent>
<owl:AllDifferent>
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 </owl:distinctMembers>
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  <rdf:Description rdf:about="#M1"/>
  <rdf:Description rdf:about="#M2"/>
  <rdf:Description rdf:about="#M3"/>
  <rdf:Description rdf:about="#M4"/>
  <rdf:Description rdf:about="#M5"/>
  <rdf:Description rdf:about="#M6"/>
  <rdf:Description rdf:about="#M7"/>
  <rdf:Description rdf:about="#M8"/>
  <rdf:Description rdf:about="#Module_9"/>
  <rdf:Description rdf:about="#Module_10"/>
  <rdf:Description rdf:about="#Module_11"/>
  <rdf:Description rdf:about="#Module_15"/>
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</owl:AllDifferent>
<owl:AllDifferent>
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  <rdf:Description rdf:about="#PhotovoltaicSystem_2"/>
 </owl:distinctMembers>
</owl:AllDifferent>
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<swrl:Variable rdf:ID="area"/>
<swrl:Variable rdf:ID="b"/>
<swrl:Variable rdf:ID="c"/>
<swrl:Variable rdf:ID="d"/>
<swrl:Variable rdf:ID="e"/>
<swrl:Variable rdf:ID="f"/>
<swrl:Variable rdf:ID="g"/>
<swrl:Variable rdf:ID="h"/>
<swrl:Variable rdf:ID="i"/>
<swrl:Variable rdf:ID="max"/>
<swrl:Variable rdf:ID="min"/>
<swrl:Variable rdf:ID="s"/>
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<swrl:Variable rdf:ID="z"/>
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 <rdfs:subClassOf rdf:resource="#Building"/>
 <owl:disjointWith rdf:resource="#CommercialBuilding"/>
 <owl:disjointWith rdf:resource="#EducationalBuilding"/>
 <owl:disjointWith rdf:resource="#IndustrialBuilding"/>
 <owl:disjointWith rdf:resource="#MilitaryBuilding"/>
 <owl:disjointWith rdf:resource="#ParkingAndStorageBuilding"/>
 <owl:disjointWith rdf:resource="#ReligiousBuilding"/>
 <owl:disjointWith rdf:resource="#ResidentialBuilding"/>
</owl:Class>
<owl:Class rdf:ID="Array">
 <rdfs:subClassOf rdf:resource="#PhotovoltaicComponent"/>
 <rdfs:subClassOf>
  <owl:Restriction>
```

```xml
    <owl:onProperty rdf:resource="#isComposedOf"/>
    <owl:someValuesFrom rdf:resource="#SubArray"/>
   </owl:Restriction>
  </rdfs:subClassOf>
  <owl:disjointWith rdf:resource="#ArraySubField"/>
  <owl:disjointWith rdf:resource="#Module"/>
  <owl:disjointWith rdf:resource="#ModulePanel"/>
  <owl:disjointWith rdf:resource="#SubArray"/>
 </owl:Class>
 <Array rdf:ID="Array_10">
  <isComponentOf rdf:resource="#ArraySubField_12"/>
  <isComponentOf rdf:resource="#GridConnected_6"/>
  <isComponentOf rdf:resource="#Hybrid_9"/>
  <isComponentOf rdf:resource="#StandAloneDC_10"/>
  <isComposedOf rdf:resource="#ArraySubField_12"/>
  <isComposedOf rdf:resource="#GridConnected_6"/>
  <isComposedOf rdf:resource="#Hybrid_9"/>
  <isComposedOf rdf:resource="#StandAloneDC_10"/>
  <isSuppliedBy rdf:resource="#Supplier_62"/>
 </Array>
 <Array rdf:ID="Array_11">
  <isComponentOf rdf:resource="#GridConnected_5"/>
 </Array>
 <owl:Class rdf:ID="ArraySubField">
  <rdfs:subClassOf rdf:resource="#PhotovoltaicComponent"/>
  <rdfs:subClassOf>
   <owl:Restriction>
    <owl:onProperty rdf:resource="#isComposedOf"/>
    <owl:someValuesFrom rdf:resource="#Array"/>
   </owl:Restriction>
  </rdfs:subClassOf>
  <owl:disjointWith rdf:resource="#Array"/>
  <owl:disjointWith rdf:resource="#Module"/>
  <owl:disjointWith rdf:resource="#ModulePanel"/>
  <owl:disjointWith rdf:resource="#SubArray"/>
 </owl:Class>
 <ArraySubField rdf:ID="ArraySubField_12">
  <isComponentOf rdf:resource="#Array_10"/>
  <isComposedOf rdf:resource="#Array_10"/>
 </ArraySubField>
 <owl:Class rdf:ID="BalanceOfComponent">
  <rdfs:subClassOf rdf:resource="#Component"/>
  <owl:disjointWith rdf:resource="#PhotovoltaicComponent"/>
 </owl:Class>
 <owl:Class rdf:ID="Battery">
  <rdfs:subClassOf rdf:resource="#ElectricalComponent"/>
  <owl:disjointWith rdf:resource="#Cable"/>
  <owl:disjointWith rdf:resource="#ChargeRegulation"/>
  <owl:disjointWith rdf:resource="#Earthing"/>
  <owl:disjointWith rdf:resource="#Fuse"/>
  <owl:disjointWith rdf:resource="#Inverter"/>
  <owl:disjointWith rdf:resource="#LightingProtection"/>
  <owl:disjointWith rdf:resource="#LowVoltageDisconnect"/>
  <owl:disjointWith rdf:resource="#MaxPowerTracker"/>
 </owl:Class>
 <Battery rdf:ID="Battery_35">
  <isComponentOf rdf:resource="#GridConnected_5"/>
 </Battery>
 <owl:Class rdf:ID="BestModuleSupplier">
  <owl:disjointWith rdf:resource="#Building"/>
```

```
&lt;owl:disjointWith rdf:resource="#BuildingConstructionSystem"/&gt;
&lt;owl:disjointWith rdf:resource="#BuildingConstructionTechnology"/&gt;
&lt;owl:disjointWith rdf:resource="#Component"/&gt;
&lt;owl:disjointWith rdf:resource="#HouseholdAppliance"/&gt;
&lt;owl:disjointWith rdf:resource="#Organisation"/&gt;
&lt;owl:disjointWith rdf:resource="&swrla;Entity"/&gt;
&lt;owl:disjointWith rdf:resource="#WorstModuleSupplier"/&gt;
&lt;/owl:Class&gt;
&lt;swrl:Imp rdf:ID="query-8.10"&gt;
 &lt;swrl:body&gt;
  &lt;swrl:AtomList&gt;
   &lt;rdf:first&gt;
    &lt;rdf:Description&gt;
     &lt;rdf:type rdf:resource="&swrl;ClassAtom"/&gt;
     &lt;swrl:argument1&gt;
      &lt;rdf:Description rdf:about="#y"/&gt;
     &lt;/swrl:argument1&gt;
     &lt;swrl:classPredicate rdf:resource="#BestModuleSupplier"/&gt;
    &lt;/rdf:Description&gt;
   &lt;/rdf:first&gt;
   &lt;rdf:rest rdf:resource="&rdf;nil"/&gt;
  &lt;/swrl:AtomList&gt;
 &lt;/swrl:body&gt;
 &lt;swrl:head&gt;
  &lt;swrl:AtomList&gt;
   &lt;rdf:first&gt;
    &lt;rdf:Description&gt;
     &lt;rdf:type rdf:resource="&swrl;BuiltinAtom"/&gt;
     &lt;swrl:arguments&gt;
      &lt;rdf:List&gt;
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        &lt;rdf:Description rdf:about="#y"/&gt;
       &lt;/rdf:first&gt;
       &lt;rdf:rest rdf:resource="&rdf;nil"/&gt;
      &lt;/rdf:List&gt;
     &lt;/swrl:arguments&gt;
     &lt;swrl:builtin&gt;
      &lt;rdf:Description rdf:about="&sqwrl;select"/&gt;
     &lt;/swrl:builtin&gt;
    &lt;/rdf:Description&gt;
   &lt;/rdf:first&gt;
   &lt;rdf:rest rdf:resource="&rdf;nil"/&gt;
  &lt;/swrl:AtomList&gt;
 &lt;/swrl:head&gt;
&lt;/swrl:Imp&gt;
&lt;swrl:Imp rdf:ID="query-8.12"&gt;
 &lt;swrl:body&gt;
  &lt;swrl:AtomList&gt;
   &lt;rdf:first&gt;
    &lt;rdf:Description&gt;
     &lt;rdf:type rdf:resource="&swrl;ClassAtom"/&gt;
     &lt;swrl:argument1&gt;
      &lt;rdf:Description rdf:about="#y"/&gt;
     &lt;/swrl:argument1&gt;
     &lt;swrl:classPredicate rdf:resource="#BestModuleSupplier"/&gt;
    &lt;/rdf:Description&gt;
   &lt;/rdf:first&gt;
   &lt;rdf:rest&gt;
    &lt;swrl:AtomList&gt;
     &lt;rdf:first&gt;
```

```xml
     <rdf:Description>
      <rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/>
      <swrl:argument2>
       <rdf:Description rdf:about="#a"/>
      </swrl:argument2>
      <swrl:argument1>
       <rdf:Description rdf:about="#y"/>
      </swrl:argument1>
      <swrl:propertyPredicate rdf:resource="#hasLocation"/>
     </rdf:Description>
    </rdf:first>
    <rdf:rest rdf:resource="&rdf;nil"/>
   </swrl:AtomList>
  </rdf:rest>
 </swrl:AtomList>
</swrl:body>
<swrl:head>
 <swrl:AtomList>
  <rdf:first>
   <rdf:Description>
    <rdf:type rdf:resource="&swrl;BuiltinAtom"/>
    <swrl:arguments>
     <rdf:List>
      <rdf:first>
       <rdf:Description rdf:about="#y"/>
      </rdf:first>
      <rdf:rest>
       <rdf:List>
        <rdf:first>
         <rdf:Description rdf:about="#a"/>
        </rdf:first>
        <rdf:rest rdf:resource="&rdf;nil"/>
       </rdf:List>
      </rdf:rest>
     </rdf:List>
    </swrl:arguments>
    <swrl:builtin>
     <rdf:Description rdf:about="&sqwrl;select"/>
    </swrl:builtin>
   </rdf:Description>
  </rdf:first>
  <rdf:rest rdf:resource="&rdf;nil"/>
 </swrl:AtomList>
</swrl:head>
</swrl:Imp>
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 <swrl:body>
  <swrl:AtomList>
   <rdf:first>
    <rdf:Description>
     <rdf:type rdf:resource="&swrl;ClassAtom"/>
     <swrl:argument1>
      <rdf:Description rdf:about="#y"/>
     </swrl:argument1>
     <swrl:classPredicate rdf:resource="#BestModuleSupplier"/>
    </rdf:Description>
   </rdf:first>
   <rdf:rest>
    <swrl:AtomList>
     <rdf:first>
```

```xml
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         <swrl:argument2>
          <rdf:Description rdf:about="#a"/>
         </swrl:argument2>
         <swrl:argument1>
          <rdf:Description rdf:about="#x"/>
         </swrl:argument1>
         <swrl:propertyPredicate rdf:resource="#hasSustainabilityIndex"/>
        </rdf:Description>
       </rdf:first>
       <rdf:rest>
        <swrl:AtomList>
         <rdf:first>
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           <rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/>
           <swrl:argument2>
            <rdf:Description rdf:about="#b"/>
           </swrl:argument2>
           <swrl:argument1>
            <rdf:Description rdf:about="#x"/>
           </swrl:argument1>
           <swrl:propertyPredicate rdf:resource="#hasCapitalCost"/>
          </rdf:Description>
         </rdf:first>
         <rdf:rest>
          <swrl:AtomList>
           <rdf:first>
            <rdf:Description>
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             <swrl:argument2>
              <rdf:Description rdf:about="#z"/>
             </swrl:argument2>
             <swrl:argument1>
              <rdf:Description rdf:about="#x"/>
             </swrl:argument1>
             <swrl:propertyPredicate rdf:resource="#hasAnnualCostSaving"/>
            </rdf:Description>
           </rdf:first>
           <rdf:rest rdf:resource="&rdf;nil"/>
          </swrl:AtomList>
         </rdf:rest>
        </swrl:AtomList>
       </rdf:rest>
      </swrl:AtomList>
     </rdf:rest>
    </swrl:AtomList>
   </swrl:body>
   <swrl:head>
    <swrl:AtomList>
     <rdf:first>
      <rdf:Description>
       <rdf:type rdf:resource="&swrl;BuiltinAtom"/>
       <swrl:arguments>
        <rdf:List>
         <rdf:first>
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         </rdf:first>
         <rdf:rest>
          <rdf:List>
```

```
        <rdf:first>
         <rdf:Description rdf:about="#y"/>
        </rdf:first>
        <rdf:rest>
         <rdf:List>
          <rdf:first>
           <rdf:Description rdf:about="#z"/>
          </rdf:first>
          <rdf:rest>
           <rdf:List>
            <rdf:first>
             <rdf:Description rdf:about="#a"/>
            </rdf:first>
            <rdf:rest>
             <rdf:List>
              <rdf:first>
               <rdf:Description rdf:about="#b"/>
              </rdf:first>
              <rdf:rest rdf:resource="&rdf;nil"/>
             </rdf:List>
            </rdf:rest>
           </rdf:List>
          </rdf:rest>
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      </rdf:rest>
     </rdf:List>
    </swrl:arguments>
    <swrl:builtin>
     <rdf:Description rdf:about="&sqwrl;select"/>
    </swrl:builtin>
   </rdf:Description>
  </rdf:first>
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</swrl:head>
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 <owl:disjointWith rdf:resource="#Geothermal"/>
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 <owl:disjointWith rdf:resource="#Solar"/>
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</owl:Class>
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 <hasBusinessExperience rdf:datatype="&xsd;int">40</hasBusinessExperience>
 <hasLocation rdf:datatype="&xsd;string">Oxford</hasLocation>
 <suppliesPhotovoltaicSystem rdf:resource="#Inverter_The_Oxford_Solar_House"/>
 <suppliesPhotovoltaicSystem rdf:resource="#Module_11"/>
 <suppliesPhotovoltaicSystem rdf:resource="#Module_The_Oxford_Solar_House"/>
 <suppliesPhotovoltaicSystem rdf:resource="#Solar_House_Array"/>
</Supplier>
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 <rdfs:subClassOf rdf:resource="#StandBy"/>
 <owl:disjointWith rdf:resource="#DeskTopComputer"/>
 <owl:disjointWith rdf:resource="#PhoneCharger"/>
 <owl:disjointWith rdf:resource="#Television"/>
</owl:Class>
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```
<owl:Class rdf:ID="Brown">
 <rdfs:subClassOf rdf:resource="#HouseholdAppliance"/>
 <owl:disjointWith rdf:resource="#Cold"/>
 <owl:disjointWith rdf:resource="#Continuous"/>
 <owl:disjointWith rdf:resource="#StandBy"/>
</owl:Class>
<owl:Class rdf:ID="Building">
 <owl:disjointWith rdf:resource="#BestModuleSupplier"/>
 <owl:disjointWith rdf:resource="#BuildingConstructionSystem"/>
 <owl:disjointWith rdf:resource="#BuildingConstructionTechnology"/>
 <owl:disjointWith rdf:resource="#Component"/>
 <owl:disjointWith rdf:resource="#HouseholdAppliance"/>
 <owl:disjointWith rdf:resource="#Organisation"/>
 <owl:disjointWith rdf:resource="&swrla;Entity"/>
 <owl:disjointWith rdf:resource="#WorstModuleSupplier"/>
</owl:Class>
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   <rdf:first>
    <rdf:Description>
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     <swrl:argument1>
      <rdf:Description rdf:about="#f"/>
     </swrl:argument1>
     <swrl:classPredicate rdf:resource="#Building"/>
    </rdf:Description>
   </rdf:first>
   <rdf:rest>
    <swrl:AtomList>
     <rdf:first>
      <rdf:Description>
       <rdf:type rdf:resource="&swrl;ClassAtom"/>
       <swrl:argument1>
        <rdf:Description rdf:about="#x"/>
       </swrl:argument1>
       <swrl:classPredicate rdf:resource="#Module"/>
      </rdf:Description>
     </rdf:first>
     <rdf:rest>
      <swrl:AtomList>
       <rdf:first>
        <rdf:Description>
         <rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/>
         <swrl:argument2>
          <rdf:Description rdf:about="#y"/>
         </swrl:argument2>
         <swrl:argument1>
          <rdf:Description rdf:about="#x"/>
         </swrl:argument1>
         <swrl:propertyPredicate rdf:resource="#hasNominalPowerOutput"/>
        </rdf:Description>
       </rdf:first>
       <rdf:rest>
        <swrl:AtomList>
         <rdf:first>
          <rdf:Description>
           <rdf:type rdf:resource="&swrl;ClassAtom"/>
           <swrl:argument1>
            <rdf:Description rdf:about="#a"/>
```

```
  </swrl:argument1>
  <swrl:classPredicate rdf:resource="#Inverter"/>
 </rdf:Description>
</rdf:first>
<rdf:rest>
 <swrl:AtomList>
  <rdf:first>
   <rdf:Description>
    <rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/>
    <swrl:argument2>
     <rdf:Description rdf:about="#e"/>
    </swrl:argument2>
    <swrl:argument1>
     <rdf:Description rdf:about="#a"/>
    </swrl:argument1>
    <swrl:propertyPredicate rdf:resource="#hasNominalPowerOutput"/>
   </rdf:Description>
  </rdf:first>
  <rdf:rest>
   <swrl:AtomList>
    <rdf:first>
     <rdf:Description>
      <rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/>
      <swrl:argument2>
       <rdf:Description rdf:about="#g"/>
      </swrl:argument2>
      <swrl:argument1>
       <rdf:Description rdf:about="#f"/>
      </swrl:argument1>
      <swrl:propertyPredicate rdf:resource="#hasDailyPeakEnergyLoad"/>
     </rdf:Description>
    </rdf:first>
    <rdf:rest>
     <swrl:AtomList>
      <rdf:first>
       <rdf:Description>
        <rdf:type rdf:resource="&swrl;BuiltinAtom"/>
        <swrl:arguments>
         <rdf:List>
          <rdf:first>
           <rdf:Description rdf:about="#y"/>
          </rdf:first>
          <rdf:rest>
           <rdf:List>
            <rdf:first>
             <rdf:Description rdf:about="#g"/>
            </rdf:first>
            <rdf:rest rdf:resource="&rdf;nil"/>
           </rdf:List>
          </rdf:rest>
         </rdf:List>
        </swrl:arguments>
        <swrl:builtin>
         <rdf:Description rdf:about="&swrlb;greaterThanOrEqual"/>
        </swrl:builtin>
       </rdf:Description>
      </rdf:first>
      <rdf:rest>
       <swrl:AtomList>
        <rdf:first>
```

```
<rdf:Description>
 <rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/>
 <swrl:argument2>
  <rdf:Description rdf:about="#z"/>
 </swrl:argument2>
 <swrl:argument1>
  <rdf:Description rdf:about="#x"/>
 </swrl:argument1>
 <swrl:propertyPredicate rdf:resource="#hasConversionEfficiency"/>
</rdf:Description>
</rdf:first>
<rdf:rest>
 <swrl:AtomList>
  <rdf:first>
   <rdf:Description>
    <rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/>
    <swrl:argument2>
     <rdf:Description rdf:about="#b"/>
    </swrl:argument2>
    <swrl:argument1>
     <rdf:Description rdf:about="#x"/>
    </swrl:argument1>
    <swrl:propertyPredicate rdf:resource="#hasPVComponentWidth"/>
   </rdf:Description>
  </rdf:first>
  <rdf:rest>
   <swrl:AtomList>
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     <rdf:Description>
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      </swrl:argument2>
      <swrl:argument1>
       <rdf:Description rdf:about="#x"/>
      </swrl:argument1>
      <swrl:propertyPredicate rdf:resource="#hasPVComponentLength"/>
     </rdf:Description>
    </rdf:first>
    <rdf:rest>
     <swrl:AtomList>
      <rdf:first>
       <rdf:Description>
        <rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/>
        <swrl:argument2>
         <rdf:Description rdf:about="#h"/>
        </swrl:argument2>
        <swrl:argument1>
         <rdf:Description rdf:about="#x"/>
        </swrl:argument1>
        <swrl:propertyPredicate rdf:resource="#hasAnnualCO2Saving"/>
       </rdf:Description>
      </rdf:first>
      <rdf:rest>
       <swrl:AtomList>
        <rdf:first>
         <rdf:Description>
          <rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/>
          <swrl:argument2>
           <rdf:Description rdf:about="#i"/>
```

```
  </swrl:argument2>
  <swrl:argument1>
   <rdf:Description rdf:about="#x"/>
  </swrl:argument1>
  <swrl:propertyPredicate rdf:resource="#hasSustainabilityIndex"/>
 </rdf:Description>
</rdf:first>
<rdf:rest>
 <swrl:AtomList>
  <rdf:first>
   <rdf:Description>
    <rdf:type rdf:resource="&swrl;BuiltinAtom"/>
    <swrl:arguments>
     <rdf:List>
      <rdf:first>
       <rdf:Description rdf:about="#area"/>
      </rdf:first>
      <rdf:rest>
       <rdf:List>
        <rdf:first rdf:datatype="&xsd;string">g/z</rdf:first>
        <rdf:rest>
         <rdf:List>
          <rdf:first>
           <rdf:Description rdf:about="#g"/>
          </rdf:first>
          <rdf:rest>
           <rdf:List>
            <rdf:first>
             <rdf:Description rdf:about="#z"/>
            </rdf:first>
            <rdf:rest rdf:resource="&rdf;nil"/>
           </rdf:List>
          </rdf:rest>
         </rdf:List>
        </rdf:rest>
       </rdf:List>
      </rdf:rest>
     </rdf:List>
    </swrl:arguments>
    <swrl:builtin>
     <rdf:Description rdf:about="&swrlm;eval"/>
    </swrl:builtin>
   </rdf:Description>
  </rdf:first>
  <rdf:rest>
   <swrl:AtomList>
    <rdf:first>
     <rdf:Description>
      <rdf:type rdf:resource="&swrl;BuiltinAtom"/>
      <swrl:arguments>
       <rdf:List>
        <rdf:first>
         <rdf:Description rdf:about="#y"/>
        </rdf:first>
        <rdf:rest>
         <rdf:List>
          <rdf:first>
           <rdf:Description rdf:about="#e"/>
          </rdf:first>
          <rdf:rest rdf:resource="&rdf;nil"/>
```

```
                          </rdf:List>
                         </rdf:rest>
                        </rdf:List>
                       </swrl:arguments>
                       <swrl:builtin>
                        <rdf:Description rdf:about="&swrlb;equal"/>
                       </swrl:builtin>
                      </rdf:Description>
                     </rdf:first>
                     <rdf:rest rdf:resource="&rdf;nil"/>
                    </swrl:AtomList>
                   </rdf:rest>
                  </swrl:AtomList>
                 </rdf:rest>
                </swrl:AtomList>
               </rdf:rest>
              </swrl:AtomList>
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            </swrl:AtomList>
           </rdf:rest>
          </swrl:AtomList>
         </rdf:rest>
        </swrl:AtomList>
       </rdf:rest>
      </swrl:AtomList>
     </rdf:rest>
    </swrl:AtomList>
   </rdf:rest>
  </swrl:AtomList>
 </rdf:rest>
</swrl:AtomList>
</swrl:body>
<swrl:head>
 <swrl:AtomList>
  <rdf:first>
   <rdf:Description>
    <rdf:type rdf:resource="&swrl;BuiltinAtom"/>
    <swrl:arguments>
     <rdf:List>
      <rdf:first>
       <rdf:Description rdf:about="#x"/>
      </rdf:first>
      <rdf:rest>
       <rdf:List>
        <rdf:first>
         <rdf:Description rdf:about="#h"/>
        </rdf:first>
        <rdf:rest>
         <rdf:List>
          <rdf:first>
           <rdf:Description rdf:about="#i"/>
          </rdf:first>
          <rdf:rest>
           <rdf:List>
```

```
<rdf:first>
 <rdf:Description rdf:about="#z"/>
</rdf:first>
<rdf:rest>
 <rdf:List>
  <rdf:first>
   <rdf:Description rdf:about="#e"/>
  </rdf:first>
  <rdf:rest>
   <rdf:List>
    <rdf:first>
     <rdf:Description rdf:about="#y"/>
    </rdf:first>
    <rdf:rest>
     <rdf:List>
      <rdf:first>
       <rdf:Description rdf:about="#g"/>
      </rdf:first>
      <rdf:rest>
       <rdf:List>
        <rdf:first>
         <rdf:Description rdf:about="#area"/>
        </rdf:first>
        <rdf:rest>
         <rdf:List>
          <rdf:first>
           <rdf:Description rdf:about="#b"/>
          </rdf:first>
          <rdf:rest>
           <rdf:List>
            <rdf:first>
             <rdf:Description rdf:about="#c"/>
            </rdf:first>
            <rdf:rest>
             <rdf:List>
              <rdf:first>
               <rdf:Description rdf:about="#a"/>
              </rdf:first>
              <rdf:rest>
               <rdf:List>
                <rdf:first>
                 <rdf:Description rdf:about="#f"/>
                </rdf:first>
                <rdf:rest rdf:resource="&rdf;nil"/>
               </rdf:List>
              </rdf:rest>
             </rdf:List>
            </rdf:rest>
           </rdf:List>
          </rdf:rest>
         </rdf:List>
        </rdf:rest>
       </rdf:List>
      </rdf:rest>
     </rdf:List>
    </rdf:rest>
   </rdf:List>
  </rdf:rest>
 </rdf:List>
</rdf:rest>
```

```
         </rdf:List>
        </rdf:rest>
       </rdf:List>
      </rdf:rest>
     </rdf:List>
    </rdf:rest>
   </rdf:List>
  </swrl:arguments>
  <swrl:builtin>
   <rdf:Description rdf:about="&sqwrl;select"/>
  </swrl:builtin>
 </rdf:Description>
 </rdf:first>
 <rdf:rest rdf:resource="&rdf;nil"/>
 </swrl:AtomList>
</swrl:head>
</swrl:Imp>
<swrl:Imp rdf:ID="query-8.16">
 <swrl:body>
  <swrl:AtomList>
   <rdf:first>
    <rdf:Description>
     <rdf:type rdf:resource="&swrl;ClassAtom"/>
     <swrl:argument1>
      <rdf:Description rdf:about="#f"/>
     </swrl:argument1>
     <swrl:classPredicate rdf:resource="#Building"/>
    </rdf:Description>
   </rdf:first>
   <rdf:rest>
    <swrl:AtomList>
     <rdf:first>
      <rdf:Description>
       <rdf:type rdf:resource="&swrl;ClassAtom"/>
       <swrl:argument1>
        <rdf:Description rdf:about="#x"/>
       </swrl:argument1>
       <swrl:classPredicate rdf:resource="#Module"/>
      </rdf:Description>
     </rdf:first>
     <rdf:rest>
      <swrl:AtomList>
       <rdf:first>
        <rdf:Description>
         <rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/>
         <swrl:argument2>
          <rdf:Description rdf:about="#y"/>
         </swrl:argument2>
         <swrl:argument1>
          <rdf:Description rdf:about="#x"/>
         </swrl:argument1>
         <swrl:propertyPredicate rdf:resource="#hasNominalPowerOutput"/>
        </rdf:Description>
       </rdf:first>
       <rdf:rest>
        <swrl:AtomList>
         <rdf:first>
          <rdf:Description>
           <rdf:type rdf:resource="&swrl;ClassAtom"/>
           <swrl:argument1>
```

```
    <rdf:Description rdf:about="#a"/>
   </swrl:argument1>
   <swrl:classPredicate rdf:resource="#Inverter"/>
  </rdf:Description>
 </rdf:first>
 <rdf:rest>
  <swrl:AtomList>
   <rdf:first>
    <rdf:Description>
     <rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/>
     <swrl:argument2>
      <rdf:Description rdf:about="#e"/>
     </swrl:argument2>
     <swrl:argument1>
      <rdf:Description rdf:about="#a"/>
     </swrl:argument1>
     <swrl:propertyPredicate rdf:resource="#hasNominalPowerOutput"/>
    </rdf:Description>
   </rdf:first>
   <rdf:rest>
    <swrl:AtomList>
     <rdf:first>
      <rdf:Description>
       <rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/>
       <swrl:argument2>
        <rdf:Description rdf:about="#g"/>
       </swrl:argument2>
       <swrl:argument1>
        <rdf:Description rdf:about="#f"/>
       </swrl:argument1>
       <swrl:propertyPredicate rdf:resource="#hasDailyPeakEnergyLoad"/>
      </rdf:Description>
     </rdf:first>
     <rdf:rest>
      <swrl:AtomList>
       <rdf:first>
        <rdf:Description>
         <rdf:type rdf:resource="&swrl;BuiltinAtom"/>
         <swrl:arguments>
          <rdf:List>
           <rdf:first>
            <rdf:Description rdf:about="#y"/>
           </rdf:first>
           <rdf:rest>
            <rdf:List>
             <rdf:first>
              <rdf:Description rdf:about="#g"/>
             </rdf:first>
             <rdf:rest rdf:resource="&rdf;nil"/>
            </rdf:List>
           </rdf:rest>
          </rdf:List>
         </swrl:arguments>
         <swrl:builtin>
          <rdf:Description rdf:about="&swrlb;greaterThanOrEqual"/>
         </swrl:builtin>
        </rdf:Description>
       </rdf:first>
       <rdf:rest>
        <swrl:AtomList>
```

```
<rdf:first>
 <rdf:Description>
  <rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/>
  <swrl:argument2>
   <rdf:Description rdf:about="#z"/>
  </swrl:argument2>
  <swrl:argument1>
   <rdf:Description rdf:about="#x"/>
  </swrl:argument1>
  <swrl:propertyPredicate rdf:resource="#hasConversionEfficiency"/>
 </rdf:Description>
</rdf:first>
<rdf:rest>
 <swrl:AtomList>
  <rdf:first>
   <rdf:Description>
    <rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/>
    <swrl:argument2>
     <rdf:Description rdf:about="#b"/>
    </swrl:argument2>
    <swrl:argument1>
     <rdf:Description rdf:about="#x"/>
    </swrl:argument1>
    <swrl:propertyPredicate rdf:resource="#hasPVComponentWidth"/>
   </rdf:Description>
  </rdf:first>
  <rdf:rest>
   <swrl:AtomList>
    <rdf:first>
     <rdf:Description>
      <rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/>
      <swrl:argument2>
       <rdf:Description rdf:about="#c"/>
      </swrl:argument2>
      <swrl:argument1>
       <rdf:Description rdf:about="#x"/>
      </swrl:argument1>
      <swrl:propertyPredicate rdf:resource="#hasPVComponentLength"/>
     </rdf:Description>
    </rdf:first>
    <rdf:rest>
     <swrl:AtomList>
      <rdf:first>
       <rdf:Description>
        <rdf:type rdf:resource="&swrl;BuiltinAtom"/>
        <swrl:arguments>
         <rdf:List>
          <rdf:first>
           <rdf:Description rdf:about="#d"/>
          </rdf:first>
          <rdf:rest>
           <rdf:List>
            <rdf:first>
             <rdf:Description rdf:about="#b"/>
            </rdf:first>
            <rdf:rest>
             <rdf:List>
              <rdf:first>
               <rdf:Description rdf:about="#c"/>
              </rdf:first>
```

```xml
        <rdf:rest rdf:resource="&rdf;nil"/>
       </rdf:List>
      </rdf:rest>
     </rdf:List>
    </rdf:rest>
   </rdf:List>
  </swrl:arguments>
  <swrl:builtin>
   <rdf:Description rdf:about="&swrlb;multiply"/>
  </swrl:builtin>
 </rdf:Description>
</rdf:first>
<rdf:rest>
 <swrl:AtomList>
  <rdf:first>
   <rdf:Description>
    <rdf:type rdf:resource="&swrl;BuiltinAtom"/>
    <swrl:arguments>
     <rdf:List>
      <rdf:first>
       <rdf:Description rdf:about="#area"/>
      </rdf:first>
      <rdf:rest>
       <rdf:List>
        <rdf:first rdf:datatype="&xsd;string">g/z</rdf:first>
        <rdf:rest>
         <rdf:List>
          <rdf:first>
           <rdf:Description rdf:about="#g"/>
          </rdf:first>
          <rdf:rest>
           <rdf:List>
            <rdf:first>
             <rdf:Description rdf:about="#z"/>
            </rdf:first>
            <rdf:rest rdf:resource="&rdf;nil"/>
           </rdf:List>
          </rdf:rest>
         </rdf:List>
        </rdf:rest>
       </rdf:List>
      </rdf:rest>
     </rdf:List>
    </swrl:arguments>
    <swrl:builtin>
     <rdf:Description rdf:about="&swrlm;eval"/>
    </swrl:builtin>
   </rdf:Description>
  </rdf:first>
  <rdf:rest>
   <swrl:AtomList>
    <rdf:first>
     <rdf:Description>
      <rdf:type rdf:resource="&swrl;BuiltinAtom"/>
      <swrl:arguments>
       <rdf:List>
        <rdf:first>
         <rdf:Description rdf:about="#y"/>
        </rdf:first>
        <rdf:rest>
```

```xml
                         <rdf:List>
                          <rdf:first>
                           <rdf:Description rdf:about="#e"/>
                          </rdf:first>
                          <rdf:rest rdf:resource="&rdf;nil"/>
                         </rdf:List>
                        </rdf:rest>
                       </rdf:List>
                      </swrl:arguments>
                      <swrl:builtin>
                       <rdf:Description rdf:about="&swrlb;equal"/>
                      </swrl:builtin>
                     </rdf:Description>
                    </rdf:first>
                    <rdf:rest rdf:resource="&rdf;nil"/>
                   </swrl:AtomList>
                  </rdf:rest>
                 </swrl:AtomList>
                </rdf:rest>
               </swrl:AtomList>
              </rdf:rest>
             </swrl:AtomList>
            </rdf:rest>
           </swrl:AtomList>
          </rdf:rest>
         </swrl:AtomList>
        </rdf:rest>
       </swrl:AtomList>
      </rdf:rest>
     </swrl:AtomList>
    </rdf:rest>
   </swrl:AtomList>
  </rdf:rest>
 </swrl:AtomList>
</rdf:rest>
</swrl:AtomList>
</swrl:body>
<swrl:head>
 <swrl:AtomList>
  <rdf:first>
   <rdf:Description>
    <rdf:type rdf:resource="&swrl;BuiltinAtom"/>
    <swrl:arguments>
     <rdf:List>
      <rdf:first>
       <rdf:Description rdf:about="#x"/>
      </rdf:first>
      <rdf:rest>
       <rdf:List>
        <rdf:first>
         <rdf:Description rdf:about="#z"/>
        </rdf:first>
        <rdf:rest>
         <rdf:List>
          <rdf:first>
           <rdf:Description rdf:about="#e"/>
```

```
</rdf:first>
<rdf:rest>
 <rdf:List>
  <rdf:first>
   <rdf:Description rdf:about="#y"/>
  </rdf:first>
  <rdf:rest>
   <rdf:List>
    <rdf:first>
     <rdf:Description rdf:about="#g"/>
    </rdf:first>
    <rdf:rest>
     <rdf:List>
      <rdf:first>
       <rdf:Description rdf:about="#area"/>
      </rdf:first>
      <rdf:rest>
       <rdf:List>
        <rdf:first>
         <rdf:Description rdf:about="#b"/>
        </rdf:first>
        <rdf:rest>
         <rdf:List>
          <rdf:first>
           <rdf:Description rdf:about="#c"/>
          </rdf:first>
          <rdf:rest>
           <rdf:List>
            <rdf:first>
             <rdf:Description rdf:about="#d"/>
            </rdf:first>
            <rdf:rest>
             <rdf:List>
              <rdf:first>
               <rdf:Description rdf:about="#a"/>
              </rdf:first>
              <rdf:rest>
               <rdf:List>
                <rdf:first>
                 <rdf:Description rdf:about="#f"/>
                </rdf:first>
                <rdf:rest rdf:resource="&rdf;nil"/>
               </rdf:List>
              </rdf:rest>
             </rdf:List>
            </rdf:rest>
           </rdf:List>
          </rdf:rest>
         </rdf:List>
        </rdf:rest>
       </rdf:List>
      </rdf:rest>
     </rdf:List>
    </rdf:rest>
   </rdf:List>
  </rdf:rest>
 </rdf:List>
</rdf:rest>
```

```
        </rdf:List>
       </rdf:rest>
      </rdf:List>
     </swrl:arguments>
     <swrl:builtin>
      <rdf:Description rdf:about="&sqwrl;select"/>
     </swrl:builtin>
    </rdf:Description>
   </rdf:first>
   <rdf:rest rdf:resource="&rdf;nil"/>
  </swrl:AtomList>
 </swrl:head>
</swrl:Imp>
<swrl:Imp rdf:ID="query-8.1">
 <swrl:body>
  <swrl:AtomList>
   <rdf:first>
    <rdf:Description>
     <rdf:type rdf:resource="&swrl;ClassAtom"/>
     <swrl:argument1>
      <rdf:Description rdf:about="#f"/>
     </swrl:argument1>
     <swrl:classPredicate rdf:resource="#Building"/>
    </rdf:Description>
   </rdf:first>
   <rdf:rest>
    <swrl:AtomList>
     <rdf:first>
      <rdf:Description>
       <rdf:type rdf:resource="&swrl;ClassAtom"/>
       <swrl:argument1>
        <rdf:Description rdf:about="#x"/>
       </swrl:argument1>
       <swrl:classPredicate rdf:resource="#Module"/>
      </rdf:Description>
     </rdf:first>
     <rdf:rest>
      <swrl:AtomList>
       <rdf:first>
        <rdf:Description>
         <rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/>
         <swrl:argument2>
          <rdf:Description rdf:about="#y"/>
         </swrl:argument2>
         <swrl:argument1>
          <rdf:Description rdf:about="#x"/>
         </swrl:argument1>
         <swrl:propertyPredicate rdf:resource="#hasNominalPowerOutput"/>
        </rdf:Description>
       </rdf:first>
       <rdf:rest>
        <swrl:AtomList>
         <rdf:first>
          <rdf:Description>
           <rdf:type rdf:resource="&swrl;ClassAtom"/>
           <swrl:argument1>
            <rdf:Description rdf:about="#a"/>
           </swrl:argument1>
           <swrl:classPredicate rdf:resource="#Inverter"/>
          </rdf:Description>
```

```
</rdf:first>
<rdf:rest>
 <swrl:AtomList>
  <rdf:first>
   <rdf:Description>
    <rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/>
    <swrl:argument2>
     <rdf:Description rdf:about="#e"/>
    </swrl:argument2>
    <swrl:argument1>
     <rdf:Description rdf:about="#a"/>
    </swrl:argument1>
    <swrl:propertyPredicate rdf:resource="#hasNominalPowerOutput"/>
   </rdf:Description>
  </rdf:first>
  <rdf:rest>
   <swrl:AtomList>
    <rdf:first>
     <rdf:Description>
      <rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/>
      <swrl:argument2>
       <rdf:Description rdf:about="#g"/>
      </swrl:argument2>
      <swrl:argument1>
       <rdf:Description rdf:about="#f"/>
      </swrl:argument1>
      <swrl:propertyPredicate rdf:resource="#hasDailyPeakEnergyLoad"/>
     </rdf:Description>
    </rdf:first>
    <rdf:rest>
     <swrl:AtomList>
      <rdf:first>
       <rdf:Description>
        <rdf:type rdf:resource="&swrl;BuiltinAtom"/>
        <swrl:arguments>
         <rdf:List>
          <rdf:first>
           <rdf:Description rdf:about="#y"/>
          </rdf:first>
          <rdf:rest>
           <rdf:List>
            <rdf:first>
             <rdf:Description rdf:about="#g"/>
            </rdf:first>
            <rdf:rest rdf:resource="&rdf;nil"/>
           </rdf:List>
          </rdf:rest>
         </rdf:List>
        </swrl:arguments>
        <swrl:builtin>
         <rdf:Description rdf:about="&swrlb;greaterThanOrEqual"/>
        </swrl:builtin>
       </rdf:Description>
      </rdf:first>
      <rdf:rest>
       <swrl:AtomList>
        <rdf:first>
         <rdf:Description>
          <rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/>
          <swrl:argument2>
```

```
<rdf:Description rdf:about="#z"/>
</swrl:argument2>
<swrl:argument1>
<rdf:Description rdf:about="#x"/>
</swrl:argument1>
<swrl:propertyPredicate rdf:resource="#hasConversionEfficiency"/>
</rdf:Description>
</rdf:first>
<rdf:rest>
<swrl:AtomList>
<rdf:first>
<rdf:Description>
<rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/>
<swrl:argument2>
<rdf:Description rdf:about="#b"/>
</swrl:argument2>
<swrl:argument1>
<rdf:Description rdf:about="#x"/>
</swrl:argument1>
<swrl:propertyPredicate rdf:resource="#hasPVComponentWidth"/>
</rdf:Description>
</rdf:first>
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<swrl:AtomList>
<rdf:first>
<rdf:Description>
<rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/>
<swrl:argument2>
<rdf:Description rdf:about="#c"/>
</swrl:argument2>
<swrl:argument1>
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</swrl:argument1>
<swrl:propertyPredicate rdf:resource="#hasPVComponentLength"/>
</rdf:Description>
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<swrl:AtomList>
<rdf:first>
<rdf:Description>
<rdf:type rdf:resource="&swrl;BuiltinAtom"/>
<swrl:arguments>
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<rdf:first>
<rdf:Description rdf:about="#area"/>
</rdf:first>
<rdf:rest>
<rdf:List>
<rdf:first rdf:datatype="&xsd;string">g/z</rdf:first>
<rdf:rest>
<rdf:List>
<rdf:first>
<rdf:Description rdf:about="#g"/>
</rdf:first>
<rdf:rest>
<rdf:List>
<rdf:first>
<rdf:Description rdf:about="#z"/>
</rdf:first>
<rdf:rest rdf:resource="&rdf;nil"/>
```

```
                            </rdf:List>
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```
>The sustainable building technology ontology is a structured
(semantics) vocabulary that describes emerging green techologies currently
being incorporated into building developments. One major advantage of the
sustainable building technology ontology is that it can be processed both
by humans and machines.</rdfs:comment>
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</owl:Class>
<owl:Class rdf:ID="Cable">
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 <owl:disjointWith rdf:resource="#Earthing"/>
 <owl:disjointWith rdf:resource="#Fuse"/>
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 &lt;suppliesPhotovoltaicSystem rdf:resource="#M3"/&gt;
&lt;/Supplier&gt;
&lt;Supplier rdf:ID="Company_3"&gt;
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&lt;/Supplier&gt;
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&lt;/Supplier&gt;
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 &lt;owl:disjointWith rdf:resource="#Building"/&gt;
 &lt;owl:disjointWith rdf:resource="#BuildingConstructionSystem"/&gt;
 &lt;owl:disjointWith rdf:resource="#BuildingConstructionTechnology"/&gt;
 &lt;owl:disjointWith rdf:resource="#HouseholdAppliance"/&gt;
 &lt;owl:disjointWith rdf:resource="#Organisation"/&gt;
 &lt;owl:disjointWith rdf:resource="&swrla;Entity"/&gt;
 &lt;owl:disjointWith rdf:resource="#WorstModuleSupplier"/&gt;
&lt;/owl:Class&gt;
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     &lt;swrl:argument1&gt;
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     &lt;/swrl:argument1&gt;
     &lt;swrl:classPredicate rdf:resource="#Component"/&gt;
    &lt;/rdf:Description&gt;
   &lt;/rdf:first&gt;
   &lt;rdf:rest&gt;
    &lt;swrl:AtomList&gt;
     &lt;rdf:first&gt;
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       &lt;swrl:argument2&gt;
        &lt;rdf:Description rdf:about="#y"/&gt;
       &lt;/swrl:argument2&gt;
       &lt;swrl:argument1&gt;
        &lt;rdf:Description rdf:about="#x"/&gt;
       &lt;/swrl:argument1&gt;
       &lt;swrl:propertyPredicate rdf:resource="#isSuppliedBy"/&gt;
      &lt;/rdf:Description&gt;
     &lt;/rdf:first&gt;
     &lt;rdf:rest&gt;
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       &lt;rdf:first&gt;
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         &lt;swrl:argument2&gt;
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       <swrl:argument1>
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       </swrl:argument1>
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  </swrl:AtomList>
 </rdf:rest>
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</swrl:body>
<swrl:head>
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        </rdf:first>
        <rdf:rest>
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          <rdf:first>
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        </rdf:rest>
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     <rdf:Description rdf:about="&sqwrl;select"/>
    </swrl:builtin>
   </rdf:Description>
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  <rdf:rest rdf:resource="&rdf;nil"/>
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 <owl:disjointWith rdf:resource="#Brown"/>
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 <owl:disjointWith rdf:resource="#StandBy"/>
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<owl:disjointWith rdf:resource="#Television"/>
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<owl:disjointWith rdf:resource="#Cable"/>
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<owl:disjointWith rdf:resource="#MaxPowerTracker"/>
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<owl:disjointWith rdf:resource="#AgriculturalBuilding"/>
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<owl:disjointWith rdf:resource="#IndustrialBuilding"/>
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<owl:disjointWith rdf:resource="#LowVoltageDisconnect"/>
<owl:disjointWith rdf:resource="#MaxPowerTracker"/>
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    <owl:Class rdf:about="#Building"/>
    <owl:Class rdf:about="#Organisation"/>
    <owl:Class rdf:about="#WorstModuleSupplier"/>
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  </owl:Class>
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 </owl:Class>
</rdfs:domain>
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  </owl:unionOf>
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</rdfs:range>
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<rdfs:range rdf:resource="&xsd;float"/>
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<rdfs:domain rdf:resource="#Module"/>
<rdfs:range rdf:resource="&xsd;float"/>
</owl:DatatypeProperty>
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     </swrl:argument2>
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 </swrl:body>
 <swrl:head>
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     <swrl:arguments>
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 &lt;/rdf:first&gt;
 &lt;rdf:rest&gt;
  &lt;rdf:List&gt;
   &lt;rdf:first&gt;
    &lt;rdf:Description rdf:about="#area"/&gt;
   &lt;/rdf:first&gt;
   &lt;rdf:rest rdf:resource="&rdf;nil"/&gt;
  &lt;/rdf:List&gt;
 &lt;/rdf:rest&gt;
&lt;/rdf:List&gt;
&lt;/swrl:arguments&gt;
&lt;swrl:builtin&gt;
 &lt;rdf:Description rdf:about="&sqwrl;select"/&gt;
&lt;/swrl:builtin&gt;
&lt;/rdf:Description&gt;
&lt;/rdf:first&gt;
&lt;rdf:rest rdf:resource="&rdf;nil"/&gt;
&lt;/swrl:AtomList&gt;
&lt;/swrl:head&gt;
&lt;/swrl:Imp&gt;
&lt;swrl:Imp rdf:ID="query-8.5"&gt;
 &lt;swrl:body&gt;
  &lt;swrl:AtomList&gt;
   &lt;rdf:first&gt;
    &lt;rdf:Description&gt;
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     &lt;swrl:argument2&gt;
      &lt;rdf:Description rdf:about="#area"/&gt;
     &lt;/swrl:argument2&gt;
     &lt;swrl:argument1&gt;
      &lt;rdf:Description rdf:about="#x"/&gt;
     &lt;/swrl:argument1&gt;
     &lt;swrl:propertyPredicate rdf:resource="#hasDesignedPV_Module"/&gt;
    &lt;/rdf:Description&gt;
   &lt;/rdf:first&gt;
   &lt;rdf:rest&gt;
    &lt;swrl:AtomList&gt;
     &lt;rdf:first&gt;
      &lt;rdf:Description&gt;
       &lt;rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/&gt;
       &lt;swrl:argument2&gt;
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       &lt;swrl:argument1&gt;
        &lt;rdf:Description rdf:about="#x"/&gt;
       &lt;/swrl:argument1&gt;
       &lt;swrl:propertyPredicate rdf:resource="#hasAnnualCO2Saving"/&gt;
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      &lt;swrl:AtomList&gt;
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        &lt;rdf:Description&gt;
         &lt;rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/&gt;
         &lt;swrl:argument2&gt;
          &lt;rdf:Description rdf:about="#z"/&gt;
         &lt;/swrl:argument2&gt;
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    <rdf:rest>
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        </swrl:argument2>
        <swrl:argument1>
         <rdf:Description rdf:about="#x"/>
        </swrl:argument1>
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      <rdf:rest>
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        <rdf:first>
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          <swrl:argument1>
           <rdf:Description rdf:about="#x"/>
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  </rdf:rest>
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</rdf:rest>
</swrl:AtomList>
</swrl:body>
<swrl:head>
 <swrl:AtomList>
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   <rdf:Description>
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    <swrl:arguments>
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      </rdf:first>
      <rdf:rest>
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        <rdf:first>
         <rdf:Description rdf:about="#z"/>
        </rdf:first>
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    <rdf:rest>
     <rdf:List>
      <rdf:first>
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      </rdf:first>
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</swrl:Imp>
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 <rdfs:range rdf:resource="&xsd;float"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="hasEnergyPayBackTime">
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   <owl:unionOf rdf:parseType="Collection">
    <owl:Class rdf:about="#PhotovoltaicComponent"/>
    <owl:Class rdf:about="#RenewableEnergyTechnology"/>
   </owl:unionOf>
  </owl:Class>
 </rdfs:domain>
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    <owl:Class rdf:about="#Building"/>
    <owl:Class rdf:about="#Organisation"/>
    <owl:Class rdf:about="#WorstModuleSupplier"/>
   </owl:unionOf>
  </owl:Class>
 </rdfs:domain>
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    <owl:Class rdf:about="#Organisation"/>
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  </owl:Class>
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       <rdf:List>
        <rdf:first rdf:datatype="&xsd;string"
         >Amorphous_Thin_Film</rdf:first>
        <rdf:rest>
         <rdf:List>
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          <rdf:rest rdf:resource="&rdf;nil"/>
         </rdf:List>
        </rdf:rest>
       </rdf:List>
      </rdf:rest>
     </rdf:List>
    </owl:oneOf>
   </owl:DataRange>
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  <rdfs:domain rdf:resource="#RenewableEnergyTechnology"/>
  <rdfs:range rdf:resource="&xsd;boolean"/>
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     <owl:Class rdf:about="#Inverter"/>
     <owl:Class rdf:about="#PhotovoltaicComponent"/>
    </owl:unionOf>
   </owl:Class>
  </rdfs:domain>
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  <rdfs:domain rdf:resource="#HouseholdAppliance"/>
  <rdfs:range rdf:resource="&xsd;int"/>
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  <rdfs:domain rdf:resource="#RenewableEnergyTechnology"/>
  <rdfs:range rdf:resource="&xsd;int"/>
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 </owl:DatatypeProperty>
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 <owl:DatatypeProperty rdf:ID="hasPostCode">
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    <owl:Class rdf:about="#BestModuleSupplier"/>
    <owl:Class rdf:about="#Building"/>
    <owl:Class rdf:about="#Organisation"/>
    <owl:Class rdf:about="#WorstModuleSupplier"/>
   </owl:unionOf>
  </owl:Class>
 </rdfs:domain>
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 <rdfs:domain rdf:resource="#Module"/>
 <rdfs:range rdf:resource="&xsd;float"/>
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<owl:DatatypeProperty rdf:ID="hasTechnicalIndex">
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 <rdfs:range rdf:resource="&xsd;boolean"/>
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 <rdfs:range rdf:resource="&xsd;boolean"/>
</owl:DatatypeProperty>
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  </owl:Class>
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    <owl:Class rdf:about="#Organisation"/>
    <owl:Class rdf:about="#WorstModuleSupplier"/>
```

```
   </owl:unionOf>
  </owl:Class>
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    <owl:Class rdf:about="#RenewableEnergyTechnology"/>
   </owl:unionOf>
  </owl:Class>
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 <owl:disjointWith rdf:resource="#BuildingConstructionSystem"/>
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 <owl:disjointWith rdf:resource="#WorstModuleSupplier"/>
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 <owl:disjointWith rdf:resource="#CommercialBuilding"/>
 <owl:disjointWith rdf:resource="#EducationalBuilding"/>
 <owl:disjointWith rdf:resource="#MilitaryBuilding"/>
 <owl:disjointWith rdf:resource="#ParkingAndStorageBuilding"/>
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 <owl:disjointWith rdf:resource="#ResidentialBuilding"/>
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</owl:Class>
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 <installsPhotovoltaicSystem rdf:resource="#M8"/>
</Installer>
<Installer rdf:ID="Installer_11">
 <installsPhotovoltaicSystem rdf:resource="#M3"/>
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<Installer rdf:ID="Installer_8"/>
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 <rdfs:range>
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   <owl:unionOf rdf:parseType="Collection">
    <owl:Class rdf:about="#Component"/>
    <owl:Class rdf:about="#RenewableEnergyTechnology"/>
   </owl:unionOf>
  </owl:Class>
 </rdfs:range>
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</owl:ObjectProperty>
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</Supplier>
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 <owl:disjointWith rdf:resource="#Cable"/>
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 <owl:disjointWith rdf:resource="#Earthing"/>
 <owl:disjointWith rdf:resource="#Fuse"/>
 <owl:disjointWith rdf:resource="#LightingProtection"/>
 <owl:disjointWith rdf:resource="#LowVoltageDisconnect"/>
 <owl:disjointWith rdf:resource="#MaxPowerTracker"/>
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 <isSuppliedBy rdf:resource="#Supplier_62"/>
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</Inverter>
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</Inverter>
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  </owl:Class>
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    <owl:Class rdf:about="#BuildingConstructionMaterial"/>
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    <owl:Class rdf:about="#RenewableEnergyTechnology"/>
   </owl:unionOf>
  </owl:Class>
 </rdfs:domain>
 <owl:inverseOf rdf:resource="#installsPhotovoltaicSystem"/>
 <rdfs:range rdf:resource="#Installer"/>
 <rdfs:subPropertyOf rdf:resource="#involvesOrganisation"/>
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<owl:ObjectProperty rdf:ID="isInvolvedIn">
 <owl:inverseOf rdf:resource="#involvesOrganisation"/>
</owl:ObjectProperty>
<owl:DatatypeProperty rdf:ID="isRecycleBle">
 <rdfs:domain>
  <owl:Class>
   <owl:unionOf rdf:parseType="Collection">
    <owl:Class rdf:about="#BuildingConstructionSystem"/>
    <owl:Class rdf:about="#BuildingConstructionTechnology"/>
    <owl:Class rdf:about="#Component"/>
   </owl:unionOf>
  </owl:Class>
 </rdfs:domain>
 <rdfs:range rdf:resource="&xsd;boolean"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="isReliable">
 <rdfs:domain>
  <owl:Class>
   <owl:unionOf rdf:parseType="Collection">
    <owl:Class rdf:about="#BuildingConstructionTechnology"/>
    <owl:Class rdf:about="#Component"/>
   </owl:unionOf>
  </owl:Class>
```

```
  </rdfs:domain>
  <rdfs:range rdf:resource="&xsd;boolean"/>
</owl:DatatypeProperty>
<owl:ObjectProperty rdf:ID="isResearchedBy">
  <rdfs:domain>
    <owl:Class>
      <owl:unionOf rdf:parseType="Collection">
        <owl:Class rdf:about="#Component"/>
        <owl:Class rdf:about="#RenewableEnergyTechnology"/>
      </owl:unionOf>
    </owl:Class>
  </rdfs:domain>
  <owl:inverseOf rdf:resource="#researchesOn"/>
  <rdfs:range rdf:resource="#Research"/>
  <rdfs:subPropertyOf rdf:resource="#involvesOrganisation"/>
</owl:ObjectProperty>
<owl:DatatypeProperty rdf:ID="isReusable">
  <rdfs:domain>
    <owl:Class>
      <owl:unionOf rdf:parseType="Collection">
        <owl:Class rdf:about="#BuildingConstructionElement"/>
        <owl:Class rdf:about="#BuildingConstructionMaterial"/>
      </owl:unionOf>
    </owl:Class>
  </rdfs:domain>
  <rdfs:range rdf:resource="&xsd;boolean"/>
</owl:DatatypeProperty>
<owl:ObjectProperty rdf:ID="isSuppliedBy">
  <rdfs:domain>
    <owl:Class>
      <owl:unionOf rdf:parseType="Collection">
        <owl:Class rdf:about="#Component"/>
        <owl:Class rdf:about="#RenewableEnergyTechnology"/>
      </owl:unionOf>
    </owl:Class>
  </rdfs:domain>
  <owl:inverseOf rdf:resource="#suppliesPhotovoltaicSystem"/>
  <rdfs:range rdf:resource="#Supplier"/>
  <rdfs:subPropertyOf rdf:resource="#involvesOrganisation"/>
</owl:ObjectProperty>
<owl:Class rdf:ID="Lighting">
  <rdfs:subClassOf rdf:resource="#Brown"/>
  <owl:disjointWith rdf:resource="#Wet"/>
</owl:Class>
<owl:Class rdf:ID="LightingProtection">
  <rdfs:subClassOf rdf:resource="#ElectricalComponent"/>
  <owl:disjointWith rdf:resource="#Battery"/>
  <owl:disjointWith rdf:resource="#Cable"/>
  <owl:disjointWith rdf:resource="#ChargeRegulation"/>
  <owl:disjointWith rdf:resource="#Earthing"/>
  <owl:disjointWith rdf:resource="#Fuse"/>
  <owl:disjointWith rdf:resource="#Inverter"/>
  <owl:disjointWith rdf:resource="#LowVoltageDisconnect"/>
  <owl:disjointWith rdf:resource="#MaxPowerTracker"/>
</owl:Class>
<owl:Class rdf:ID="LowVoltageDisconnect">
  <rdfs:subClassOf rdf:resource="#ElectricalComponent"/>
  <owl:disjointWith rdf:resource="#Battery"/>
  <owl:disjointWith rdf:resource="#Cable"/>
  <owl:disjointWith rdf:resource="#ChargeRegulation"/>
```

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 <owl:disjointWith rdf:resource="#Earthing"/>
 <owl:disjointWith rdf:resource="#Fuse"/>
 <owl:disjointWith rdf:resource="#Inverter"/>
 <owl:disjointWith rdf:resource="#LightingProtection"/>
 <owl:disjointWith rdf:resource="#MaxPowerTracker"/>
</owl:Class>
<Module rdf:ID="M1">
 <hasAnnualCO2Saving rdf:datatype="&xsd;float">1300.0</hasAnnualCO2Saving>
 <hasAnnualCostSaving rdf:datatype="&xsd;int">400</hasAnnualCostSaving>
 <hasCapitalCost rdf:datatype="&xsd;int">9000</hasCapitalCost>
 <hasConversionEfficiency rdf:datatype="&xsd;float">0.147</hasConversionEfficiency>
 <hasEconomicIndex rdf:datatype="&xsd;float">0.3</hasEconomicIndex>
 <hasEnergyPayBackTime rdf:datatype="&xsd;int">8</hasEnergyPayBackTime>
 <hasEnvironmentalIndex rdf:datatype="&xsd;float">0.93</hasEnvironmentalIndex>
 <hasLeadFreeLevel rdf:datatype="&xsd;float">0.0</hasLeadFreeLevel>
 <hasMaterialType rdf:datatype="&xsd;string">Monocrystalline</hasMaterialType>
 <hasModuleArea rdf:datatype="&xsd;float">1.26</hasModuleArea>
 <hasNominalPowerOutput rdf:datatype="&xsd;float">0.185</hasNominalPowerOutput>
 <hasPhysicalIndex rdf:datatype="&xsd;float">0.09</hasPhysicalIndex>
 <hasPVComponentLength rdf:datatype="&xsd;float">1.575</hasPVComponentLength>
 <hasPVComponentWidth rdf:datatype="&xsd;float">0.8</hasPVComponentWidth>
 <hasSocialIndex rdf:datatype="&xsd;float">0.0</hasSocialIndex>
 <hasSustainabilityIndex rdf:datatype="&xsd;float">0.6</hasSustainabilityIndex>
 <hasTechnicalIndex rdf:datatype="&xsd;float">1.0</hasTechnicalIndex>
 <hasWarranty rdf:datatype="&xsd;int">25</hasWarranty>
 <hasWeight rdf:datatype="&xsd;float">14.5</hasWeight>
 <isResearchedBy rdf:resource="#Oxford_University"/>
 <isSuppliedBy rdf:resource="#Company_1"/>
</Module>
<Module rdf:ID="M2">
 <hasAnnualCO2Saving rdf:datatype="&xsd;float">1100.0</hasAnnualCO2Saving>
 <hasAnnualCostSaving rdf:datatype="&xsd;int">300</hasAnnualCostSaving>
 <hasCapitalCost rdf:datatype="&xsd;int">8000</hasCapitalCost>
 <hasConversionEfficiency rdf:datatype="&xsd;float">0.12</hasConversionEfficiency>
 <hasEconomicIndex rdf:datatype="&xsd;float">0.47</hasEconomicIndex>
 <hasEnergyPayBackTime rdf:datatype="&xsd;int">8</hasEnergyPayBackTime>
 <hasEnvironmentalIndex rdf:datatype="&xsd;float">0.15</hasEnvironmentalIndex>
 <hasLeadFreeLevel rdf:datatype="&xsd;float">0.0</hasLeadFreeLevel>
 <hasMaterialType rdf:datatype="&xsd;string">Monocrystalline</hasMaterialType>
 <hasModuleArea rdf:datatype="&xsd;float">0.47</hasModuleArea>
 <hasNominalPowerOutput rdf:datatype="&xsd;float">0.065</hasNominalPowerOutput>
 <hasPhysicalIndex rdf:datatype="&xsd;float">0.96</hasPhysicalIndex>
 <hasPVComponentLength rdf:datatype="&xsd;float">0.734</hasPVComponentLength>
 <hasPVComponentWidth rdf:datatype="&xsd;float">0.634</hasPVComponentWidth>
 <hasSocialIndex rdf:datatype="&xsd;float">0.47</hasSocialIndex>
 <hasSustainabilityIndex rdf:datatype="&xsd;float">0.39</hasSustainabilityIndex>
 <hasTechnicalIndex rdf:datatype="&xsd;float">0.62</hasTechnicalIndex>
 <hasWarranty rdf:datatype="&xsd;int">25</hasWarranty>
 <hasWeight rdf:datatype="&xsd;float">6.5</hasWeight>
 <isResearchedBy rdf:resource="#Oxford_University"/>
 <isSuppliedBy rdf:resource="#Company_2"/>
</Module>
<Module rdf:ID="M3">
 <hasAnnualCO2Saving rdf:datatype="&xsd;float">1000.0</hasAnnualCO2Saving>
 <hasAnnualCostSaving rdf:datatype="&xsd;int">200</hasAnnualCostSaving>
 <hasCapitalCost rdf:datatype="&xsd;int">6500</hasCapitalCost>
 <hasConversionEfficiency rdf:datatype="&xsd;float">0.11</hasConversionEfficiency>
 <hasEconomicIndex rdf:datatype="&xsd;float">0.38</hasEconomicIndex>
 <hasEnergyPayBackTime rdf:datatype="&xsd;int">8</hasEnergyPayBackTime>
 <hasEnvironmentalIndex rdf:datatype="&xsd;float">0.08</hasEnvironmentalIndex>
```

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 <hasLeadFreeLevel rdf:datatype="&xsd;float">0.0</hasLeadFreeLevel>
 <hasMaterialType rdf:datatype="&xsd;string">Monocrystalline</hasMaterialType>
 <hasModuleArea rdf:datatype="&xsd;float">0.47</hasModuleArea>
 <hasNominalPowerOutput rdf:datatype="&xsd;float">0.06</hasNominalPowerOutput>
 <hasPhysicalIndex rdf:datatype="&xsd;float">1.0</hasPhysicalIndex>
 <hasPVComponentLength rdf:datatype="&xsd;float">0.734</hasPVComponentLength>
 <hasPVComponentWidth rdf:datatype="&xsd;float">0.634</hasPVComponentWidth>
 <hasSocialIndex rdf:datatype="&xsd;float">0.47</hasSocialIndex>
 <hasSustainabilityIndex rdf:datatype="&xsd;float">0.32</hasSustainabilityIndex>
 <hasTechnicalIndex rdf:datatype="&xsd;float">0.48</hasTechnicalIndex>
 <hasWarranty rdf:datatype="&xsd;int">25</hasWarranty>
 <hasWeight rdf:datatype="&xsd;float">3.5</hasWeight>
 <isInstalledBy rdf:resource="#Installer_11"/>
 <isResearchedBy rdf:resource="#Oxford_University"/>
 <isSuppliedBy rdf:resource="#Company_2"/>
</Module>
<Module rdf:ID="M4">
 <hasAnnualCO2Saving rdf:datatype="&xsd;float">1290.0</hasAnnualCO2Saving>
 <hasAnnualCostSaving rdf:datatype="&xsd;int">355</hasAnnualCostSaving>
 <hasCapitalCost rdf:datatype="&xsd;int">8800</hasCapitalCost>
 <hasConversionEfficiency rdf:datatype="&xsd;float">0.141</hasConversionEfficiency>
 <hasEconomicIndex rdf:datatype="&xsd;float">0.41</hasEconomicIndex>
 <hasEnergyPayBackTime rdf:datatype="&xsd;int">8</hasEnergyPayBackTime>
 <hasEnvironmentalIndex rdf:datatype="&xsd;float">0.93</hasEnvironmentalIndex>
 <hasLeadFreeLevel rdf:datatype="&xsd;float">0.0</hasLeadFreeLevel>
 <hasMaterialType rdf:datatype="&xsd;string">Monocrystalline</hasMaterialType>
 <hasModuleArea rdf:datatype="&xsd;float">1.31</hasModuleArea>
 <hasNominalPowerOutput rdf:datatype="&xsd;float">0.185</hasNominalPowerOutput>
 <hasPhysicalIndex rdf:datatype="&xsd;float">0.02</hasPhysicalIndex>
 <hasPVComponentLength rdf:datatype="&xsd;float">1.318</hasPVComponentLength>
 <hasPVComponentWidth rdf:datatype="&xsd;float">0.994</hasPVComponentWidth>
 <hasSocialIndex rdf:datatype="&xsd;float">1.0</hasSocialIndex>
 <hasSustainabilityIndex rdf:datatype="&xsd;float">0.73</hasSustainabilityIndex>
 <hasTechnicalIndex rdf:datatype="&xsd;float">0.91</hasTechnicalIndex>
 <hasWarranty rdf:datatype="&xsd;int">20</hasWarranty>
 <hasWeight rdf:datatype="&xsd;float">16.0</hasWeight>
 <isResearchedBy rdf:resource="#Oxford_University"/>
 <isSuppliedBy rdf:resource="#Company_3"/>
</Module>
<Module rdf:ID="M5">
 <hasAnnualCO2Saving rdf:datatype="&xsd;float">1000.0</hasAnnualCO2Saving>
 <hasAnnualCostSaving rdf:datatype="&xsd;int">200</hasAnnualCostSaving>
 <hasCapitalCost rdf:datatype="&xsd;int">7500</hasCapitalCost>
 <hasConversionEfficiency rdf:datatype="&xsd;float">0.13</hasConversionEfficiency>
 <hasEconomicIndex rdf:datatype="&xsd;float">0.35</hasEconomicIndex>
 <hasEnergyPayBackTime rdf:datatype="&xsd;int">2</hasEnergyPayBackTime>
 <hasEnvironmentalIndex rdf:datatype="&xsd;float">0.72</hasEnvironmentalIndex>
 <hasLeadFreeLevel rdf:datatype="&xsd;float">0.0</hasLeadFreeLevel>
 <hasMaterialType rdf:datatype="&xsd;string">Polycrystalline</hasMaterialType>
 <hasModuleArea rdf:datatype="&xsd;float">1.31</hasModuleArea>
 <hasNominalPowerOutput rdf:datatype="&xsd;float">0.17</hasNominalPowerOutput>
 <hasPhysicalIndex rdf:datatype="&xsd;float">0.02</hasPhysicalIndex>
 <hasSocialIndex rdf:datatype="&xsd;float">1.0</hasSocialIndex>
 <hasSustainabilityIndex rdf:datatype="&xsd;float">0.62</hasSustainabilityIndex>
 <hasTechnicalIndex rdf:datatype="&xsd;float">0.76</hasTechnicalIndex>
 <hasWarranty rdf:datatype="&xsd;int">20</hasWarranty>
 <hasWeight rdf:datatype="&xsd;float">16.0</hasWeight>
 <isResearchedBy rdf:resource="#Oxford_University"/>
 <isSuppliedBy rdf:resource="#Company_3"/>
</Module>
```

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<Module rdf:ID="M6">
 <hasAnnualCO2Saving rdf:datatype="&xsd;float">800.0</hasAnnualCO2Saving>
 <hasAnnualCostSaving rdf:datatype="&xsd;int">150</hasAnnualCostSaving>
 <hasCapitalCost rdf:datatype="&xsd;int">5000</hasCapitalCost>
 <hasConversionEfficiency rdf:datatype="&xsd;float">0.076</hasConversionEfficiency>
 <hasEnergyPayBackTime rdf:datatype="&xsd;int">3</hasEnergyPayBackTime>
 <hasEnvironmentalIndex rdf:datatype="&xsd;float">0.12</hasEnvironmentalIndex>
 <hasEnvironmentalIndex rdf:datatype="&xsd;float">0.44</hasEnvironmentalIndex>
 <hasLeadFreeLevel rdf:datatype="&xsd;float">0.0</hasLeadFreeLevel>
 <hasMaterialType rdf:datatype="&xsd;string"
  >Amorphous_Thin_Film</hasMaterialType>
 <hasModuleArea rdf:datatype="&xsd;float">1.05</hasModuleArea>
 <hasNominalPowerOutput rdf:datatype="&xsd;float">0.08</hasNominalPowerOutput>
 <hasPhysicalIndex rdf:datatype="&xsd;float">0.26</hasPhysicalIndex>
 <hasPVComponentLength rdf:datatype="&xsd;float">1.129</hasPVComponentLength>
 <hasPVComponentWidth rdf:datatype="&xsd;float">0.934</hasPVComponentWidth>
 <hasSocialIndex rdf:datatype="&xsd;float">1.0</hasSocialIndex>
 <hasSustainabilityIndex rdf:datatype="&xsd;float">0.37</hasSustainabilityIndex>
 <hasTechnicalIndex rdf:datatype="&xsd;float">0.0</hasTechnicalIndex>
 <hasWarranty rdf:datatype="&xsd;int">20</hasWarranty>
 <hasWeight rdf:datatype="&xsd;float">18.0</hasWeight>
 <isResearchedBy rdf:resource="#Oxford_University"/>
 <isSuppliedBy rdf:resource="#Company_3"/>
 <rdfs:comment rdf:datatype="&xsd;string"></rdfs:comment>
</Module>
<Module rdf:ID="M7">
 <hasAnnualCO2Saving rdf:datatype="&xsd;float">950.0</hasAnnualCO2Saving>
 <hasAnnualCostSaving rdf:datatype="&xsd;int">215</hasAnnualCostSaving>
 <hasCapitalCost rdf:datatype="&xsd;int">6500</hasCapitalCost>
 <hasConversionEfficiency rdf:datatype="&xsd;float">0.129</hasConversionEfficiency>
 <hasEconomicIndex rdf:datatype="&xsd;float">0.52</hasEconomicIndex>
 <hasEnergyPayBackTime rdf:datatype="&xsd;int">2</hasEnergyPayBackTime>
 <hasEnvironmentalIndex rdf:datatype="&xsd;float">0.55</hasEnvironmentalIndex>
 <hasLeadFreeLevel rdf:datatype="&xsd;float">100.0</hasLeadFreeLevel>
 <hasMaterialType rdf:datatype="&xsd;string">Polycrystalline</hasMaterialType>
 <hasModuleArea rdf:datatype="&xsd;float">1.01</hasModuleArea>
 <hasNominalPowerOutput rdf:datatype="&xsd;float">0.13</hasNominalPowerOutput>
 <hasPhysicalIndex rdf:datatype="&xsd;float">0.36</hasPhysicalIndex>
 <hasPVComponentLength rdf:datatype="&xsd;float">1.495</hasPVComponentLength>
 <hasPVComponentWidth rdf:datatype="&xsd;float">0.674</hasPVComponentWidth>
 <hasSocialIndex rdf:datatype="&xsd;float">0.61</hasSocialIndex>
 <hasSustainabilityIndex rdf:datatype="&xsd;float">0.55</hasSustainabilityIndex>
 <hasTechnicalIndex rdf:datatype="&xsd;float">0.75</hasTechnicalIndex>
 <hasWarranty rdf:datatype="&xsd;int">25</hasWarranty>
 <hasWeight rdf:datatype="&xsd;float">13.0</hasWeight>
 <isResearchedBy rdf:resource="#Oxford_University"/>
 <isSuppliedBy rdf:resource="#Company_4"/>
 <rdfs:comment rdf:datatype="&xsd;string"
  >Contains the most complete data</rdfs:comment>
</Module>
<Module rdf:ID="M8">
 <hasAnnualCO2Saving rdf:datatype="&xsd;float">900.0</hasAnnualCO2Saving>
 <hasAnnualCostSaving rdf:datatype="&xsd;int">190</hasAnnualCostSaving>
 <hasCapitalCost rdf:datatype="&xsd;int">6700</hasCapitalCost>
 <hasConversionEfficiency rdf:datatype="&xsd;float">0.114</hasConversionEfficiency>
 <hasEconomicIndex rdf:datatype="&xsd;float">0.46</hasEconomicIndex>
 <hasEnergyPayBackTime rdf:datatype="&xsd;int">2</hasEnergyPayBackTime>
 <hasEnvironmentalIndex rdf:datatype="&xsd;float">0.44</hasEnvironmentalIndex>
 <hasLeadFreeLevel rdf:datatype="&xsd;float">100.0</hasLeadFreeLevel>
 <hasMaterialType rdf:datatype="&xsd;string">Polycrystalline</hasMaterialType>
```

```xml
<hasModuleArea rdf:datatype="&xsd;float">1.01</hasModuleArea>
<hasNominalPowerOutput rdf:datatype="&xsd;float">0.115</hasNominalPowerOutput>
<hasPhysicalIndex rdf:datatype="&xsd;float">0.35</hasPhysicalIndex>
<hasPVComponentLength rdf:datatype="&xsd;float">1.495</hasPVComponentLength>
<hasPVComponentWidth rdf:datatype="&xsd;float">0.674</hasPVComponentWidth>
<hasSocialIndex rdf:datatype="&xsd;float">0.61</hasSocialIndex>
<hasSustainabilityIndex rdf:datatype="&xsd;float">0.49</hasSustainabilityIndex>
<hasTechnicalIndex rdf:datatype="&xsd;float">0.54</hasTechnicalIndex>
<hasWarranty rdf:datatype="&xsd;int">25</hasWarranty>
<hasWeight rdf:datatype="&xsd;float">13.5</hasWeight>
<isInstalledBy rdf:resource="#Installer_10"/>
<isResearchedBy rdf:resource="#Oxford_University"/>
<isSuppliedBy rdf:resource="#Company_4"/>
<rdfs:comment rdf:datatype="&xsd;string"
 >Contains the most complete data</rdfs:comment>
</Module>
<owl:Class rdf:ID="MaxPowerTracker">
 <rdfs:subClassOf rdf:resource="#ElectricalComponent"/>
 <owl:disjointWith rdf:resource="#Battery"/>
 <owl:disjointWith rdf:resource="#Cable"/>
 <owl:disjointWith rdf:resource="#ChargeRegulation"/>
 <owl:disjointWith rdf:resource="#Earthing"/>
 <owl:disjointWith rdf:resource="#Fuse"/>
 <owl:disjointWith rdf:resource="#Inverter"/>
 <owl:disjointWith rdf:resource="#LightingProtection"/>
 <owl:disjointWith rdf:resource="#LowVoltageDisconnect"/>
</owl:Class>
<owl:Class rdf:ID="MechanicalComponent">
 <rdfs:subClassOf rdf:resource="#BalanceOfComponent"/>
 <owl:disjointWith rdf:resource="#ElectricalComponent"/>
</owl:Class>
<owl:Class rdf:ID="MilitaryBuilding">
 <rdfs:subClassOf rdf:resource="#Building"/>
 <owl:disjointWith rdf:resource="#AgriculturalBuilding"/>
 <owl:disjointWith rdf:resource="#CommercialBuilding"/>
 <owl:disjointWith rdf:resource="#EducationalBuilding"/>
 <owl:disjointWith rdf:resource="#IndustrialBuilding"/>
 <owl:disjointWith rdf:resource="#ParkingAndStorageBuilding"/>
 <owl:disjointWith rdf:resource="#ReligiousBuilding"/>
 <owl:disjointWith rdf:resource="#ResidentialBuilding"/>
</owl:Class>
<owl:Class rdf:ID="ModernMethodsOfConstruction">
 <rdfs:subClassOf rdf:resource="#BuildingConstructionSystem"/>
 <owl:disjointWith rdf:resource="#TraditionalMethodsOfConstruction"/>
</owl:Class>
<owl:Class rdf:ID="Module">
 <rdfs:subClassOf rdf:resource="#PhotovoltaicComponent"/>
 <rdfs:subClassOf>
  <owl:Restriction>
   <owl:onProperty rdf:resource="#hasMaterialType"/>
   <owl:cardinality rdf:datatype="&xsd;nonNegativeInteger">1</owl:cardinality>
  </owl:Restriction>
 </rdfs:subClassOf>
 <owl:disjointWith rdf:resource="#Array"/>
 <owl:disjointWith rdf:resource="#ArraySubField"/>
 <owl:disjointWith rdf:resource="#ModulePanel"/>
 <owl:disjointWith rdf:resource="#SubArray"/>
 <rdfs:comment rdf:datatype="&xsd;string"
  >A module is the smallest complete environmentally
protected assembly of interconnected solar cells.</rdfs:comment>
```

```xml
</owl:Class>
<swrl:Imp rdf:ID="Rule-8.2">
 <swrl:body>
  <swrl:AtomList>
   <rdf:first>
    <rdf:Description>
     <rdf:type rdf:resource="&swrl;ClassAtom"/>
     <swrl:argument1>
      <rdf:Description rdf:about="#x"/>
     </swrl:argument1>
     <swrl:classPredicate rdf:resource="#Module"/>
    </rdf:Description>
   </rdf:first>
   <rdf:rest>
    <swrl:AtomList>
     <rdf:first>
      <rdf:Description>
       <rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/>
       <swrl:argument2>
        <rdf:Description rdf:about="#y"/>
       </swrl:argument2>
       <swrl:argument1>
        <rdf:Description rdf:about="#x"/>
       </swrl:argument1>
       <swrl:propertyPredicate rdf:resource="#hasNominalPowerOutput"/>
      </rdf:Description>
     </rdf:first>
     <rdf:rest>
      <swrl:AtomList>
       <rdf:first>
        <rdf:Description>
         <rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/>
         <swrl:argument2>
          <rdf:Description rdf:about="#z"/>
         </swrl:argument2>
         <swrl:argument1>
          <rdf:Description rdf:about="#x"/>
         </swrl:argument1>
         <swrl:propertyPredicate rdf:resource="#hasConversionEfficiency"/>
        </rdf:Description>
       </rdf:first>
       <rdf:rest>
        <swrl:AtomList>
         <rdf:first>
          <rdf:Description>
           <rdf:type rdf:resource="&swrl;ClassAtom"/>
           <swrl:argument1>
            <rdf:Description rdf:about="#a"/>
           </swrl:argument1>
           <swrl:classPredicate rdf:resource="#Inverter"/>
          </rdf:Description>
         </rdf:first>
         <rdf:rest>
          <swrl:AtomList>
           <rdf:first>
            <rdf:Description>
             <rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/>
             <swrl:argument2>
              <rdf:Description rdf:about="#e"/>
             </swrl:argument2>
```

```
&lt;swrl:argument1&gt;
 &lt;rdf:Description rdf:about="#a"/&gt;
&lt;/swrl:argument1&gt;
&lt;swrl:propertyPredicate rdf:resource="#hasNominalPowerOutput"/&gt;
&lt;/rdf:Description&gt;
&lt;/rdf:first&gt;
&lt;rdf:rest&gt;
&lt;swrl:AtomList&gt;
 &lt;rdf:first&gt;
  &lt;rdf:Description&gt;
  &lt;rdf:type rdf:resource="&swrl;ClassAtom"/&gt;
  &lt;swrl:argument1&gt;
   &lt;rdf:Description rdf:about="#g"/&gt;
  &lt;/swrl:argument1&gt;
  &lt;swrl:classPredicate rdf:resource="#HouseholdAppliance"/&gt;
  &lt;/rdf:Description&gt;
 &lt;/rdf:first&gt;
 &lt;rdf:rest&gt;
  &lt;swrl:AtomList&gt;
  &lt;rdf:first&gt;
   &lt;rdf:Description&gt;
   &lt;rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/&gt;
   &lt;swrl:argument2&gt;
    &lt;rdf:Description rdf:about="#h"/&gt;
   &lt;/swrl:argument2&gt;
   &lt;swrl:argument1&gt;
    &lt;rdf:Description rdf:about="#g"/&gt;
   &lt;/swrl:argument1&gt;
   &lt;swrl:propertyPredicate rdf:resource="#hasPowerRating"/&gt;
   &lt;/rdf:Description&gt;
  &lt;/rdf:first&gt;
  &lt;rdf:rest&gt;
   &lt;swrl:AtomList&gt;
   &lt;rdf:first&gt;
    &lt;rdf:Description&gt;
    &lt;rdf:type rdf:resource="&swrl;BuiltinAtom"/&gt;
    &lt;swrl:arguments&gt;
     &lt;rdf:List&gt;
     &lt;rdf:first&gt;
      &lt;rdf:Description rdf:about="#s"/&gt;
     &lt;/rdf:first&gt;
     &lt;rdf:rest&gt;
      &lt;rdf:List&gt;
      &lt;rdf:first&gt;
       &lt;rdf:Description rdf:about="#h"/&gt;
      &lt;/rdf:first&gt;
      &lt;rdf:rest rdf:resource="&rdf;nil"/&gt;
      &lt;/rdf:List&gt;
     &lt;/rdf:rest&gt;
     &lt;/rdf:List&gt;
    &lt;/swrl:arguments&gt;
    &lt;swrl:builtin&gt;
     &lt;rdf:Description rdf:about="&sqwrl;makeSet"/&gt;
    &lt;/swrl:builtin&gt;
    &lt;/rdf:Description&gt;
   &lt;/rdf:first&gt;
   &lt;rdf:rest&gt;
    &lt;swrl:AtomList&gt;
    &lt;rdf:first&gt;
     &lt;rdf:Description&gt;
```

```
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  <swrl:arguments>
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     <rdf:Description rdf:about="#sum"/>
    </rdf:first>
    <rdf:rest>
     <rdf:List>
      <rdf:first>
       <rdf:Description rdf:about="#s"/>
      </rdf:first>
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     </rdf:List>
    </rdf:rest>
   </rdf:List>
  </swrl:arguments>
  <swrl:builtin>
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  </swrl:builtin>
 </rdf:Description>
</rdf:first>
<rdf:rest>
 <swrl:AtomList>
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   <rdf:Description>
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    <swrl:arguments>
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       <rdf:Description rdf:about="#e"/>
      </rdf:first>
      <rdf:rest>
       <rdf:List>
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        </rdf:first>
        <rdf:rest rdf:resource="&rdf;nil"/>
       </rdf:List>
      </rdf:rest>
     </rdf:List>
    </swrl:arguments>
    <swrl:builtin>
     <rdf:Description rdf:about="&swrlb;equal"/>
    </swrl:builtin>
   </rdf:Description>
  </rdf:first>
  <rdf:rest>
   <swrl:AtomList>
    <rdf:first>
     <rdf:Description>
      <rdf:type rdf:resource="&swrl;BuiltinAtom"/>
      <swrl:arguments>
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        <rdf:first>
         <rdf:Description rdf:about="#y"/>
        </rdf:first>
        <rdf:rest>
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          <rdf:first>
           <rdf:Description rdf:about="#sum"/>
```

```
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</rdf:rest>
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<swrl:builtin>
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</swrl:builtin>
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<swrl:AtomList>
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<rdf:Description>
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<swrl:arguments>
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<rdf:first>
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</rdf:rest>
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</rdf:rest>
```

```
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        </rdf:rest>
       </swrl:AtomList>
      </rdf:rest>
     </swrl:AtomList>
    </rdf:rest>
   </swrl:AtomList>
  </swrl:body>
  <swrl:head>
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      </swrl:argument2>
      <swrl:argument1>
       <rdf:Description rdf:about="#x"/>
      </swrl:argument1>
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     </rdf:Description>
    </rdf:first>
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      </swrl:argument1>
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    </rdf:first>
    <rdf:rest>
     <swrl:AtomList>
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       <rdf:Description>
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        <swrl:argument2>
         <rdf:Description rdf:about="#y"/>
        </swrl:argument2>
        <swrl:argument1>
         <rdf:Description rdf:about="#x"/>
        </swrl:argument1>
        <swrl:propertyPredicate rdf:resource="#hasNominalPowerOutput"/>
       </rdf:Description>
      </rdf:first>
      <rdf:rest>
       <swrl:AtomList>
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         <rdf:Description>
          <rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/>
          <swrl:argument2>
           <rdf:Description rdf:about="#z"/>
          </swrl:argument2>
```

```
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 </swrl:argument1>
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<rdf:rest>
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  <rdf:first>
   <rdf:Description>
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    </swrl:argument1>
    <swrl:classPredicate rdf:resource="#Inverter"/>
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  <rdf:rest>
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     <rdf:Description>
      <rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/>
      <swrl:argument2>
       <rdf:Description rdf:about="#e"/>
      </swrl:argument2>
      <swrl:argument1>
       <rdf:Description rdf:about="#a"/>
      </swrl:argument1>
      <swrl:propertyPredicate rdf:resource="#hasNominalPowerOutput"/>
     </rdf:Description>
    </rdf:first>
    <rdf:rest>
     <swrl:AtomList>
      <rdf:first>
       <rdf:Description>
        <rdf:type rdf:resource="&swrl;ClassAtom"/>
        <swrl:argument1>
         <rdf:Description rdf:about="#g"/>
        </swrl:argument1>
        <swrl:classPredicate rdf:resource="#HouseholdAppliance"/>
       </rdf:Description>
      </rdf:first>
      <rdf:rest>
       <swrl:AtomList>
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         <rdf:Description>
          <rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/>
          <swrl:argument2>
           <rdf:Description rdf:about="#h"/>
          </swrl:argument2>
          <swrl:argument1>
           <rdf:Description rdf:about="#g"/>
          </swrl:argument1>
          <swrl:propertyPredicate rdf:resource="#hasPowerRating"/>
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        <rdf:rest>
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           <rdf:Description>
```

```
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  </rdf:first>
  <rdf:rest>
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     <rdf:Description rdf:about="#h"/>
    </rdf:first>
    <rdf:rest rdf:resource="&rdf;nil"/>
   </rdf:List>
  </rdf:rest>
 </rdf:List>
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<swrl:builtin>
 <rdf:Description rdf:about="&sqwrl;makeSet"/>
</swrl:builtin>
</rdf:Description>
</rdf:first>
<rdf:rest>
 <swrl:AtomList>
  <rdf:first>
   <rdf:Description>
    <rdf:type rdf:resource="&swrl;BuiltinAtom"/>
    <swrl:arguments>
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      <rdf:first>
       <rdf:Description rdf:about="#sum"/>
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        </rdf:first>
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      </rdf:rest>
     </rdf:List>
    </swrl:arguments>
    <swrl:builtin>
     <rdf:Description rdf:about="&sqwrl;sum"/>
    </swrl:builtin>
   </rdf:Description>
  </rdf:first>
  <rdf:rest>
   <swrl:AtomList>
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     <rdf:Description>
      <rdf:type rdf:resource="&swrl;BuiltinAtom"/>
      <swrl:arguments>
       <rdf:List>
        <rdf:first>
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        </rdf:first>
        <rdf:rest>
         <rdf:List>
          <rdf:first>
           <rdf:Description rdf:about="#y"/>
```

```
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       <rdf:rest rdf:resource="&rdf;nil"/>
      </rdf:List>
     </rdf:rest>
    </rdf:List>
   </swrl:arguments>
   <swrl:builtin>
    <rdf:Description rdf:about="&swrlb;equal"/>
   </swrl:builtin>
  </rdf:Description>
 </rdf:first>
 <rdf:rest>
  <swrl:AtomList>
   <rdf:first>
    <rdf:Description>
     <rdf:type rdf:resource="&swrl;BuiltinAtom"/>
     <swrl:arguments>
      <rdf:List>
       <rdf:first>
        <rdf:Description rdf:about="#y"/>
       </rdf:first>
       <rdf:rest>
        <rdf:List>
         <rdf:first>
          <rdf:Description rdf:about="#sum"/>
         </rdf:first>
         <rdf:rest rdf:resource="&rdf;nil"/>
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       </rdf:rest>
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      <rdf:Description>
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          <rdf:Description rdf:about="#area"/>
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         <rdf:rest>
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           <rdf:first>
            <rdf:Description rdf:about="#sum"/>
           </rdf:first>
           <rdf:rest>
            <rdf:List>
             <rdf:first>
              <rdf:Description rdf:about="#z"/>
             </rdf:first>
             <rdf:rest rdf:resource="&rdf;nil"/>
            </rdf:List>
           </rdf:rest>
          </rdf:List>
```

```xml
                            </rdf:rest>
                           </rdf:List>
                          </swrl:arguments>
                          <swrl:builtin>
                           <rdf:Description rdf:about="&swrlb;divide"/>
                          </swrl:builtin>
                         </rdf:Description>
                        </rdf:first>
                        <rdf:rest rdf:resource="&rdf;nil"/>
                       </swrl:AtomList>
                      </rdf:rest>
                     </swrl:AtomList>
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    </rdf:rest>
   </swrl:AtomList>
  </rdf:rest>
 </swrl:AtomList>
</swrl:body>
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    <rdf:type rdf:resource="&swrl;BuiltinAtom"/>
    <swrl:arguments>
     <rdf:List>
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       <rdf:Description rdf:about="#x"/>
      </rdf:first>
      <rdf:rest>
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        <rdf:first>
         <rdf:Description rdf:about="#a"/>
        </rdf:first>
        <rdf:rest>
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          <rdf:rest>
           <rdf:List>
            <rdf:first>
             <rdf:Description rdf:about="#e"/>
            </rdf:first>
            <rdf:rest>
             <rdf:List>
```

```
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</rdf:first>
<rdf:rest>
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  <rdf:first>
   <rdf:Description rdf:about="#area"/>
  </rdf:first>
  <rdf:rest rdf:resource="&rdf;nil"/>
 </rdf:List>
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</rdf:rest>
</rdf:List>
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<swrl:builtin>
 <rdf:Description rdf:about="&sqwrl;select"/>
</swrl:builtin>
</rdf:Description>
</rdf:first>
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</swrl:Imp>
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 <swrl:body>
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      <rdf:Description rdf:about="#x"/>
     </swrl:argument1>
     <swrl:classPredicate rdf:resource="#Module"/>
    </rdf:Description>
   </rdf:first>
   <rdf:rest>
    <swrl:AtomList>
     <rdf:first>
      <rdf:Description>
       <rdf:type rdf:resource="&swrl;IndividualPropertyAtom"/>
       <swrl:argument2>
        <rdf:Description rdf:about="#b"/>
       </swrl:argument2>
       <swrl:argument1>
        <rdf:Description rdf:about="#x"/>
       </swrl:argument1>
       <swrl:propertyPredicate rdf:resource="#isSuppliedBy"/>
      </rdf:Description>
     </rdf:first>
     <rdf:rest>
      <swrl:AtomList>
       <rdf:first>
        <rdf:Description>
```

```
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</swrl:argument2>
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</swrl:argument1>
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</rdf:Description>
</rdf:first>
<rdf:rest>
 <swrl:AtomList>
  <rdf:first>
   <rdf:Description>
    <rdf:type rdf:resource="&swrl;BuiltinAtom"/>
    <swrl:arguments>
     <rdf:List>
      <rdf:first>
       <rdf:Description rdf:about="#s"/>
      </rdf:first>
      <rdf:rest>
       <rdf:List>
        <rdf:first>
         <rdf:Description rdf:about="#a"/>
        </rdf:first>
        <rdf:rest rdf:resource="&rdf;nil"/>
       </rdf:List>
      </rdf:rest>
     </rdf:List>
    </swrl:arguments>
    <swrl:builtin>
     <rdf:Description rdf:about="&sqwrl;makeSet"/>
    </swrl:builtin>
   </rdf:Description>
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     <rdf:Description>
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      <swrl:builtin>
       <rdf:Description rdf:about="&sqwrl;max"/>
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     </rdf:Description>
    </rdf:first>
```

```
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              </rdf:first>
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            </swrl:arguments>
            <swrl:builtin>
             <rdf:Description rdf:about="&swrlb;equal"/>
            </swrl:builtin>
           </rdf:Description>
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<swrl:head>
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    <rdf:type rdf:resource="&swrl;BuiltinAtom"/>
    <swrl:arguments>
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      <rdf:first>
       <rdf:Description rdf:about="#x"/>
      </rdf:first>
      <rdf:rest>
       <rdf:List>
        <rdf:first>
         <rdf:Description rdf:about="#a"/>
        </rdf:first>
        <rdf:rest>
         <rdf:List>
          <rdf:first>
           <rdf:Description rdf:about="#b"/>
          </rdf:first>
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         </rdf:List>
```

```
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       &lt;/rdf:List&gt;
      &lt;/rdf:rest&gt;
     &lt;/rdf:List&gt;
    &lt;/swrl:arguments&gt;
    &lt;swrl:builtin&gt;
     &lt;rdf:Description rdf:about="&sqwrl;select"/&gt;
    &lt;/swrl:builtin&gt;
   &lt;/rdf:Description&gt;
  &lt;/rdf:first&gt;
  &lt;rdf:rest rdf:resource="&rdf;nil"/&gt;
 &lt;/swrl:AtomList&gt;
&lt;/swrl:head&gt;
&lt;/swrl:Imp&gt;
&lt;swrl:Imp rdf:ID="query-8.13"&gt;
 &lt;swrl:body&gt;
  &lt;swrl:AtomList&gt;
   &lt;rdf:first&gt;
    &lt;rdf:Description&gt;
     &lt;rdf:type rdf:resource="&swrl;ClassAtom"/&gt;
     &lt;swrl:argument1&gt;
      &lt;rdf:Description rdf:about="#x"/&gt;
     &lt;/swrl:argument1&gt;
     &lt;swrl:classPredicate rdf:resource="#Module"/&gt;
    &lt;/rdf:Description&gt;
   &lt;/rdf:first&gt;
   &lt;rdf:rest&gt;
    &lt;swrl:AtomList&gt;
     &lt;rdf:first&gt;
      &lt;rdf:Description&gt;
       &lt;rdf:type rdf:resource="&swrl;IndividualPropertyAtom"/&gt;
       &lt;swrl:argument2&gt;
        &lt;rdf:Description rdf:about="#b"/&gt;
       &lt;/swrl:argument2&gt;
       &lt;swrl:argument1&gt;
        &lt;rdf:Description rdf:about="#x"/&gt;
       &lt;/swrl:argument1&gt;
       &lt;swrl:propertyPredicate rdf:resource="#isSuppliedBy"/&gt;
      &lt;/rdf:Description&gt;
     &lt;/rdf:first&gt;
     &lt;rdf:rest&gt;
      &lt;swrl:AtomList&gt;
       &lt;rdf:first&gt;
        &lt;rdf:Description&gt;
         &lt;rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/&gt;
         &lt;swrl:argument2&gt;
          &lt;rdf:Description rdf:about="#a"/&gt;
         &lt;/swrl:argument2&gt;
         &lt;swrl:argument1&gt;
          &lt;rdf:Description rdf:about="#x"/&gt;
         &lt;/swrl:argument1&gt;
         &lt;swrl:propertyPredicate rdf:resource="#hasSustainabilityIndex"/&gt;
        &lt;/rdf:Description&gt;
       &lt;/rdf:first&gt;
       &lt;rdf:rest&gt;
        &lt;swrl:AtomList&gt;
         &lt;rdf:first&gt;
          &lt;rdf:Description&gt;
           &lt;rdf:type rdf:resource="&swrl;BuiltinAtom"/&gt;
           &lt;swrl:arguments&gt;
```

```
      <rdf:List>
       <rdf:first>
        <rdf:Description rdf:about="#s"/>
       </rdf:first>
       <rdf:rest>
        <rdf:List>
         <rdf:first>
          <rdf:Description rdf:about="#a"/>
         </rdf:first>
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        </rdf:List>
       </rdf:rest>
      </rdf:List>
     </swrl:arguments>
     <swrl:builtin>
      <rdf:Description rdf:about="&sqwrl;makeSet"/>
     </swrl:builtin>
    </rdf:Description>
   </rdf:first>
   <rdf:rest>
    <swrl:AtomList>
     <rdf:first>
      <rdf:Description>
       <rdf:type rdf:resource="&swrl;BuiltinAtom"/>
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          <rdf:Description rdf:about="#min"/>
         </rdf:first>
         <rdf:rest>
          <rdf:List>
           <rdf:first>
            <rdf:Description rdf:about="#s"/>
           </rdf:first>
           <rdf:rest rdf:resource="&rdf;nil"/>
          </rdf:List>
         </rdf:rest>
        </rdf:List>
       </swrl:arguments>
       <swrl:builtin>
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       </swrl:builtin>
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     </rdf:first>
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         <rdf:type rdf:resource="&swrl;BuiltinAtom"/>
         <swrl:arguments>
          <rdf:List>
           <rdf:first>
            <rdf:Description rdf:about="#a"/>
           </rdf:first>
           <rdf:rest>
            <rdf:List>
             <rdf:first>
              <rdf:Description rdf:about="#min"/>
             </rdf:first>
             <rdf:rest rdf:resource="&rdf;nil"/>
```

```
                  </rdf:List>
                 </rdf:rest>
                </rdf:List>
               </swrl:arguments>
               <swrl:builtin>
                <rdf:Description rdf:about="&swrlb;equal"/>
               </swrl:builtin>
              </rdf:Description>
             </rdf:first>
             <rdf:rest rdf:resource="&rdf;nil"/>
            </swrl:AtomList>
           </rdf:rest>
          </swrl:AtomList>
         </rdf:rest>
        </swrl:AtomList>
       </rdf:rest>
      </swrl:AtomList>
     </rdf:rest>
    </swrl:AtomList>
   </rdf:rest>
  </swrl:AtomList>
 </swrl:body>
 <swrl:head>
  <swrl:AtomList>
   <rdf:first>
    <rdf:Description>
     <rdf:type rdf:resource="&swrl;BuiltinAtom"/>
     <swrl:arguments>
      <rdf:List>
       <rdf:first>
        <rdf:Description rdf:about="#x"/>
       </rdf:first>
       <rdf:rest>
        <rdf:List>
         <rdf:first>
          <rdf:Description rdf:about="#a"/>
         </rdf:first>
         <rdf:rest>
          <rdf:List>
           <rdf:first>
            <rdf:Description rdf:about="#b"/>
           </rdf:first>
           <rdf:rest rdf:resource="&rdf;nil"/>
          </rdf:List>
         </rdf:rest>
        </rdf:List>
       </rdf:rest>
      </rdf:List>
     </swrl:arguments>
     <swrl:builtin>
      <rdf:Description rdf:about="&sqwrl;select"/>
     </swrl:builtin>
    </rdf:Description>
   </rdf:first>
   <rdf:rest rdf:resource="&rdf;nil"/>
  </swrl:AtomList>
 </swrl:head>
</swrl:Imp>
<swrl:Imp rdf:ID="query-8.17">
 <swrl:body>
```

```
<swrl:AtomList>
 <rdf:first>
  <rdf:Description>
   <rdf:type rdf:resource="&swrl;ClassAtom"/>
   <swrl:argument1>
    <rdf:Description rdf:about="#x"/>
   </swrl:argument1>
   <swrl:classPredicate rdf:resource="#Module"/>
  </rdf:Description>
 </rdf:first>
 <rdf:rest>
  <swrl:AtomList>
   <rdf:first>
    <rdf:Description>
     <rdf:type rdf:resource="&swrl;IndividualPropertyAtom"/>
     <swrl:argument2>
      <rdf:Description rdf:about="#b"/>
     </swrl:argument2>
     <swrl:argument1>
      <rdf:Description rdf:about="#x"/>
     </swrl:argument1>
     <swrl:propertyPredicate rdf:resource="#isSuppliedBy"/>
    </rdf:Description>
   </rdf:first>
   <rdf:rest>
    <swrl:AtomList>
     <rdf:first>
      <rdf:Description>
       <rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/>
       <swrl:argument2>
        <rdf:Description rdf:about="#a"/>
       </swrl:argument2>
       <swrl:argument1>
        <rdf:Description rdf:about="#x"/>
       </swrl:argument1>
       <swrl:propertyPredicate rdf:resource="#hasSustainabilityIndex"/>
      </rdf:Description>
     </rdf:first>
     <rdf:rest>
      <swrl:AtomList>
       <rdf:first>
        <rdf:Description>
         <rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/>
         <swrl:argument2>
          <rdf:Description rdf:about="#y"/>
         </swrl:argument2>
         <swrl:argument1>
          <rdf:Description rdf:about="#x"/>
         </swrl:argument1>
         <swrl:propertyPredicate rdf:resource="#hasAnnualCostSaving"/>
        </rdf:Description>
       </rdf:first>
       <rdf:rest>
        <swrl:AtomList>
         <rdf:first>
          <rdf:Description>
           <rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/>
           <swrl:argument2>
            <rdf:Description rdf:about="#z"/>
           </swrl:argument2>
```

```xml
<swrl:argument1>
<rdf:Description rdf:about="#x"/>
</swrl:argument1>
<swrl:propertyPredicate rdf:resource="#hasCapitalCost"/>
</rdf:Description>
</rdf:first>
<rdf:rest>
<swrl:AtomList>
<rdf:first>
<rdf:Description>
<rdf:type rdf:resource="&swrl;BuiltinAtom"/>
<swrl:arguments>
<rdf:List>
<rdf:first>
<rdf:Description rdf:about="#s"/>
</rdf:first>
<rdf:rest>
<rdf:List>
<rdf:first>
<rdf:Description rdf:about="#a"/>
</rdf:first>
<rdf:rest rdf:resource="&rdf;nil"/>
</rdf:List>
</rdf:rest>
</rdf:List>
</swrl:arguments>
<swrl:builtin>
<rdf:Description rdf:about="&sqwrl;makeSet"/>
</swrl:builtin>
</rdf:Description>
</rdf:first>
<rdf:rest>
<swrl:AtomList>
<rdf:first>
<rdf:Description>
<rdf:type rdf:resource="&swrl;BuiltinAtom"/>
<swrl:arguments>
<rdf:List>
<rdf:first>
<rdf:Description rdf:about="#max"/>
</rdf:first>
<rdf:rest>
<rdf:List>
<rdf:first>
<rdf:Description rdf:about="#s"/>
</rdf:first>
<rdf:rest rdf:resource="&rdf;nil"/>
</rdf:List>
</rdf:rest>
</rdf:List>
</swrl:arguments>
<swrl:builtin>
<rdf:Description rdf:about="&sqwrl;max"/>
</swrl:builtin>
</rdf:Description>
</rdf:first>
<rdf:rest>
<swrl:AtomList>
<rdf:first>
<rdf:Description>
```

```
            <rdf:type rdf:resource="&swrl;BuiltinAtom"/>
            <swrl:arguments>
             <rdf:List>
              <rdf:first>
               <rdf:Description rdf:about="#a"/>
              </rdf:first>
              <rdf:rest>
               <rdf:List>
                <rdf:first>
                 <rdf:Description rdf:about="#max"/>
                </rdf:first>
                <rdf:rest rdf:resource="&rdf;nil"/>
               </rdf:List>
              </rdf:rest>
             </rdf:List>
            </swrl:arguments>
            <swrl:builtin>
             <rdf:Description rdf:about="&swrlb;equal"/>
            </swrl:builtin>
           </rdf:Description>
          </rdf:first>
          <rdf:rest rdf:resource="&rdf;nil"/>
         </swrl:AtomList>
        </rdf:rest>
       </swrl:AtomList>
      </rdf:rest>
     </swrl:AtomList>
    </rdf:rest>
   </swrl:AtomList>
  </rdf:rest>
 </swrl:AtomList>
</rdf:rest>
</swrl:AtomList>
</rdf:rest>
</swrl:AtomList>
</swrl:body>
<swrl:head>
 <swrl:AtomList>
  <rdf:first>
   <rdf:Description>
    <rdf:type rdf:resource="&swrl;BuiltinAtom"/>
    <swrl:arguments>
     <rdf:List>
      <rdf:first>
       <rdf:Description rdf:about="#x"/>
      </rdf:first>
      <rdf:rest>
       <rdf:List>
        <rdf:first>
         <rdf:Description rdf:about="#a"/>
        </rdf:first>
        <rdf:rest>
         <rdf:List>
          <rdf:first>
           <rdf:Description rdf:about="#z"/>
          </rdf:first>
          <rdf:rest>
           <rdf:List>
```

```xml
           <rdf:first>
            <rdf:Description rdf:about="#y"/>
           </rdf:first>
           <rdf:rest>
            <rdf:List>
             <rdf:first>
              <rdf:Description rdf:about="#b"/>
             </rdf:first>
             <rdf:rest rdf:resource="&rdf;nil"/>
            </rdf:List>
           </rdf:rest>
          </rdf:List>
         </rdf:rest>
        </rdf:List>
       </rdf:rest>
      </rdf:List>
     </rdf:rest>
    </rdf:List>
   </swrl:arguments>
   <swrl:builtin>
    <rdf:Description rdf:about="&sqwrl;select"/>
   </swrl:builtin>
  </rdf:Description>
 </rdf:first>
 <rdf:rest rdf:resource="&rdf;nil"/>
 </swrl:AtomList>
</swrl:head>
</swrl:Imp>
<swrl:Imp rdf:ID="Rule-8.3">
 <swrl:body>
  <swrl:AtomList>
   <rdf:first>
    <rdf:Description>
     <rdf:type rdf:resource="&swrl;ClassAtom"/>
     <swrl:argument1>
      <rdf:Description rdf:about="#x"/>
     </swrl:argument1>
     <swrl:classPredicate rdf:resource="#Module"/>
    </rdf:Description>
   </rdf:first>
   <rdf:rest>
    <swrl:AtomList>
     <rdf:first>
      <rdf:Description>
       <rdf:type rdf:resource="&swrl;IndividualPropertyAtom"/>
       <swrl:argument2>
        <rdf:Description rdf:about="#y"/>
       </swrl:argument2>
       <swrl:argument1>
        <rdf:Description rdf:about="#x"/>
       </swrl:argument1>
       <swrl:propertyPredicate rdf:resource="#isSuppliedBy"/>
      </rdf:Description>
     </rdf:first>
     <rdf:rest>
      <swrl:AtomList>
       <rdf:first>
        <rdf:Description>
         <rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/>
         <swrl:argument2>
```

```
<rdf:Description rdf:about="#a"/>
</swrl:argument2>
<swrl:argument1>
<rdf:Description rdf:about="#x"/>
</swrl:argument1>
<swrl:propertyPredicate rdf:resource="#hasSustainabilityIndex"/>
</rdf:Description>
</rdf:first>
<rdf:rest>
<swrl:AtomList>
<rdf:first>
<rdf:Description>
<rdf:type rdf:resource="&swrl;BuiltinAtom"/>
<swrl:arguments>
<rdf:List>
<rdf:first>
<rdf:Description rdf:about="#s"/>
</rdf:first>
<rdf:rest>
<rdf:List>
<rdf:first>
<rdf:Description rdf:about="#a"/>
</rdf:first>
<rdf:rest rdf:resource="&rdf;nil"/>
</rdf:List>
</rdf:rest>
</rdf:List>
</swrl:arguments>
<swrl:builtin>
<rdf:Description rdf:about="&sqwrl;makeSet"/>
</swrl:builtin>
</rdf:Description>
</rdf:first>
<rdf:rest>
<swrl:AtomList>
<rdf:first>
<rdf:Description>
<rdf:type rdf:resource="&swrl;BuiltinAtom"/>
<swrl:arguments>
<rdf:List>
<rdf:first>
<rdf:Description rdf:about="#max"/>
</rdf:first>
<rdf:rest>
<rdf:List>
<rdf:first>
<rdf:Description rdf:about="#s"/>
</rdf:first>
<rdf:rest rdf:resource="&rdf;nil"/>
</rdf:List>
</rdf:rest>
</rdf:List>
</swrl:arguments>
<swrl:builtin>
<rdf:Description rdf:about="&sqwrl;max"/>
</swrl:builtin>
</rdf:Description>
</rdf:first>
<rdf:rest>
<swrl:AtomList>
```

```
             <rdf:first>
              <rdf:Description>
               <rdf:type rdf:resource="&swrl;BuiltinAtom"/>
               <swrl:arguments>
                <rdf:List>
                 <rdf:first>
                  <rdf:Description rdf:about="#a"/>
                 </rdf:first>
                 <rdf:rest>
                  <rdf:List>
                   <rdf:first>
                    <rdf:Description rdf:about="#max"/>
                   </rdf:first>
                   <rdf:rest rdf:resource="&rdf;nil"/>
                  </rdf:List>
                 </rdf:rest>
                </rdf:List>
               </swrl:arguments>
               <swrl:builtin>
                <rdf:Description rdf:about="&swrlb;equal"/>
               </swrl:builtin>
              </rdf:Description>
             </rdf:first>
             <rdf:rest rdf:resource="&rdf;nil"/>
            </swrl:AtomList>
           </rdf:rest>
          </swrl:AtomList>
         </rdf:rest>
        </swrl:AtomList>
       </rdf:rest>
      </swrl:AtomList>
     </rdf:rest>
    </swrl:AtomList>
   </rdf:rest>
  </swrl:AtomList>
 </swrl:body>
 <swrl:head>
  <swrl:AtomList>
   <rdf:first>
    <rdf:Description>
     <rdf:type rdf:resource="&swrl;ClassAtom"/>
     <swrl:argument1>
      <rdf:Description rdf:about="#y"/>
     </swrl:argument1>
     <swrl:classPredicate rdf:resource="#BestModuleSupplier"/>
    </rdf:Description>
   </rdf:first>
   <rdf:rest rdf:resource="&rdf;nil"/>
  </swrl:AtomList>
 </swrl:head>
</swrl:Imp>
<swrl:Imp rdf:ID="Rule-8.4">
 <swrl:body>
  <swrl:AtomList>
   <rdf:first>
    <rdf:Description>
     <rdf:type rdf:resource="&swrl;ClassAtom"/>
     <swrl:argument1>
      <rdf:Description rdf:about="#x"/>
     </swrl:argument1>
```

```
<swrl:classPredicate rdf:resource="#Module"/>
</rdf:Description>
</rdf:first>
<rdf:rest>
<swrl:AtomList>
<rdf:first>
<rdf:Description>
<rdf:type rdf:resource="&swrl;IndividualPropertyAtom"/>
<swrl:argument2>
<rdf:Description rdf:about="#y"/>
</swrl:argument2>
<swrl:argument1>
<rdf:Description rdf:about="#x"/>
</swrl:argument1>
<swrl:propertyPredicate rdf:resource="#isSuppliedBy"/>
</rdf:Description>
</rdf:first>
<rdf:rest>
<swrl:AtomList>
<rdf:first>
<rdf:Description>
<rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/>
<swrl:argument2>
<rdf:Description rdf:about="#a"/>
</swrl:argument2>
<swrl:argument1>
<rdf:Description rdf:about="#x"/>
</swrl:argument1>
<swrl:propertyPredicate rdf:resource="#hasSustainabilityIndex"/>
</rdf:Description>
</rdf:first>
<rdf:rest>
<swrl:AtomList>
<rdf:first>
<rdf:Description>
<rdf:type rdf:resource="&swrl;BuiltinAtom"/>
<swrl:arguments>
<rdf:List>
<rdf:first>
<rdf:Description rdf:about="#s"/>
</rdf:first>
<rdf:rest>
<rdf:List>
<rdf:first>
<rdf:Description rdf:about="#a"/>
</rdf:first>
<rdf:rest rdf:resource="&rdf;nil"/>
</rdf:List>
</rdf:rest>
</rdf:List>
</swrl:arguments>
<swrl:builtin>
<rdf:Description rdf:about="&sqwrl;makeSet"/>
</swrl:builtin>
</rdf:Description>
</rdf:first>
<rdf:rest>
<swrl:AtomList>
<rdf:first>
<rdf:Description>
```

```
        <rdf:type rdf:resource="&swrl;BuiltinAtom"/>
        <swrl:arguments>
         <rdf:List>
          <rdf:first>
           <rdf:Description rdf:about="#min"/>
          </rdf:first>
          <rdf:rest>
           <rdf:List>
            <rdf:first>
             <rdf:Description rdf:about="#s"/>
            </rdf:first>
            <rdf:rest rdf:resource="&rdf;nil"/>
           </rdf:List>
          </rdf:rest>
         </rdf:List>
        </swrl:arguments>
        <swrl:builtin>
         <rdf:Description rdf:about="&sqwrl;min"/>
        </swrl:builtin>
       </rdf:Description>
      </rdf:first>
      <rdf:rest>
       <swrl:AtomList>
        <rdf:first>
         <rdf:Description>
          <rdf:type rdf:resource="&swrl;BuiltinAtom"/>
          <swrl:arguments>
           <rdf:List>
            <rdf:first>
             <rdf:Description rdf:about="#a"/>
            </rdf:first>
            <rdf:rest>
             <rdf:List>
              <rdf:first>
               <rdf:Description rdf:about="#min"/>
              </rdf:first>
              <rdf:rest rdf:resource="&rdf;nil"/>
             </rdf:List>
            </rdf:rest>
           </rdf:List>
          </swrl:arguments>
          <swrl:builtin>
           <rdf:Description rdf:about="&swrlb;equal"/>
          </swrl:builtin>
         </rdf:Description>
        </rdf:first>
        <rdf:rest rdf:resource="&rdf;nil"/>
       </swrl:AtomList>
      </rdf:rest>
     </swrl:AtomList>
    </rdf:rest>
   </swrl:AtomList>
  </rdf:rest>
 </swrl:AtomList>
</rdf:rest>
</swrl:AtomList>
</rdf:rest>
</swrl:AtomList>
</swrl:body>
<swrl:head>
```

```
   <swrl:AtomList>
    <rdf:first>
     <rdf:Description>
      <rdf:type rdf:resource="&swrl;ClassAtom"/>
      <swrl:argument1>
       <rdf:Description rdf:about="#y"/>
      </swrl:argument1>
      <swrl:classPredicate rdf:resource="#WorstModuleSupplier"/>
     </rdf:Description>
    </rdf:first>
    <rdf:rest rdf:resource="&rdf;nil"/>
   </swrl:AtomList>
  </swrl:head>
 </swrl:Imp>
 <Module rdf:ID="Module_10"/>
 <Module rdf:ID="Module_11">
  <hasAnnualCostSaving rdf:datatype="&xsd;int">500</hasAnnualCostSaving>
  <hasCapitalCost rdf:datatype="&xsd;int">5666</hasCapitalCost>
  <hasConversionEfficiency rdf:datatype="&xsd;float">0.15</hasConversionEfficiency>
  <hasMaterialType rdf:datatype="&xsd;string">Polycrystalline</hasMaterialType>
  <hasNominalPowerOutput rdf:datatype="&xsd;float">5.0</hasNominalPowerOutput>
  <hasSustainabilityIndex rdf:datatype="&xsd;float">0.62</hasSustainabilityIndex>
  <isSuppliedBy rdf:resource="#BP_Solar"/>
 </Module>
 <Module rdf:ID="Module_12"/>
 <Module rdf:ID="Module_13">
  <isComponentOf rdf:resource="#PhotovoltaicSystem_2"/>
 </Module>
 <Module rdf:ID="Module_14">
  <hasMaterialType rdf:datatype="&xsd;string"
  >Amorphous_Thin_Film</hasMaterialType>
  <hasSustainabilityIndex rdf:datatype="&xsd;float">0.31999</hasSustainabilityIndex>
  <isSuppliedBy rdf:resource="#Supplier_62"/>
 </Module>
 <Module rdf:ID="Module_15">
  <hasMaterialType rdf:datatype="&xsd;string"
  >Amorphous_Thin_Film</hasMaterialType>
  <isComponentOf rdf:resource="#ModulePanel_18"/>
  <isSuppliedBy rdf:resource="#Intelligent_Energy_Solutions_Ltd"/>
 </Module>
 <Module rdf:ID="Module_9">
  <hasConversionEfficiency rdf:datatype="&xsd;float">0.14</hasConversionEfficiency>
  <hasModuleArea rdf:datatype="&xsd;float">30.0</hasModuleArea>
  <hasNominalPowerOutput rdf:datatype="&xsd;float">4.0</hasNominalPowerOutput>
  <hasPVComponentLength rdf:datatype="&xsd;float">6.0</hasPVComponentLength>
  <hasPVComponentWidth rdf:datatype="&xsd;float">5.0</hasPVComponentWidth>
 </Module>
 <Module rdf:ID="Module_The_Oxford_Solar_House">
  <hasAnnualCO2Saving rdf:datatype="&xsd;float">4870.0</hasAnnualCO2Saving>
  <hasConversionEfficiency rdf:datatype="&xsd;float">0.145</hasConversionEfficiency>
  <hasLeadFreeLevel rdf:datatype="&xsd;float">100.0</hasLeadFreeLevel>
  <hasMaterialType rdf:datatype="&xsd;string">Monocrystalline</hasMaterialType>
  <hasNominalPowerOutput rdf:datatype="&xsd;float">4.0</hasNominalPowerOutput>
  <hasPVComponentLength rdf:datatype="&xsd;float">6.8</hasPVComponentLength>
  <hasPVComponentWidth rdf:datatype="&xsd;float">5.0</hasPVComponentWidth>
  <hasSustainabilityIndex rdf:datatype="&xsd;float">0.6</hasSustainabilityIndex>
  <hasWarranty rdf:datatype="&xsd;int">25</hasWarranty>
  <hasWeight rdf:datatype="&xsd;float">6.1</hasWeight>
  <isComponentOf rdf:resource="#PhotovoltaicSystem_The_Solar_House"/>
  <isComponentOf rdf:resource="#Solar_House_Array"/>
```

```
&lt;isRecycleBle rdf:datatype="&xsd;boolean"&gt;true&lt;/isRecycleBle&gt;
&lt;isReliable rdf:datatype="&xsd;boolean"&gt;true&lt;/isReliable&gt;
&lt;isSuppliedBy rdf:resource="#BP_Solar"/&gt;
&lt;/Module&gt;
&lt;owl:Class rdf:ID="ModulePanel"&gt;
&lt;rdfs:subClassOf rdf:resource="#PhotovoltaicComponent"/&gt;
&lt;rdfs:subClassOf&gt;
 &lt;owl:Restriction&gt;
  &lt;owl:onProperty rdf:resource="#isComposedOf"/&gt;
  &lt;owl:someValuesFrom rdf:resource="#Module"/&gt;
 &lt;/owl:Restriction&gt;
&lt;/rdfs:subClassOf&gt;
&lt;owl:disjointWith rdf:resource="#Array"/&gt;
&lt;owl:disjointWith rdf:resource="#ArraySubField"/&gt;
&lt;owl:disjointWith rdf:resource="#Module"/&gt;
&lt;owl:disjointWith rdf:resource="#SubArray"/&gt;
&lt;/owl:Class&gt;
&lt;ModulePanel rdf:ID="ModulePanel_18"&gt;
&lt;isComposedOf rdf:resource="#Module_15"/&gt;
&lt;/ModulePanel&gt;
&lt;owl:Class rdf:ID="MovingMounting"&gt;
&lt;rdfs:subClassOf rdf:resource="#MechanicalComponent"/&gt;
&lt;owl:disjointWith rdf:resource="#FixedMounting"/&gt;
&lt;/owl:Class&gt;
&lt;MovingMounting rdf:ID="MovingMounting_55"&gt;
&lt;isComponentOf rdf:resource="#GridConnected_5"/&gt;
&lt;/MovingMounting&gt;
&lt;owl:Class rdf:ID="NonGridConnected"&gt;
&lt;rdfs:subClassOf rdf:resource="#PhotovoltaicSystem"/&gt;
&lt;/owl:Class&gt;
&lt;owl:Class rdf:ID="Organisation"&gt;
&lt;owl:disjointWith rdf:resource="#BestModuleSupplier"/&gt;
&lt;owl:disjointWith rdf:resource="#Building"/&gt;
&lt;owl:disjointWith rdf:resource="#BuildingConstructionSystem"/&gt;
&lt;owl:disjointWith rdf:resource="#BuildingConstructionTechnology"/&gt;
&lt;owl:disjointWith rdf:resource="#Component"/&gt;
&lt;owl:disjointWith rdf:resource="#HouseholdAppliance"/&gt;
&lt;owl:disjointWith rdf:resource="&swrla;Entity"/&gt;
&lt;owl:disjointWith rdf:resource="#WorstModuleSupplier"/&gt;
&lt;/owl:Class&gt;
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&lt;researchesOn rdf:resource="#M1"/&gt;
&lt;researchesOn rdf:resource="#M2"/&gt;
&lt;researchesOn rdf:resource="#M3"/&gt;
&lt;researchesOn rdf:resource="#M4"/&gt;
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&lt;researchesOn rdf:resource="#PhotovoltaicSystem_The_Solar_House"/&gt;
&lt;/Research&gt;
&lt;owl:Class rdf:ID="ParkingAndStorageBuilding"&gt;
&lt;rdfs:subClassOf rdf:resource="#Building"/&gt;
&lt;owl:disjointWith rdf:resource="#AgriculturalBuilding"/&gt;
&lt;owl:disjointWith rdf:resource="#CommercialBuilding"/&gt;
&lt;owl:disjointWith rdf:resource="#EducationalBuilding"/&gt;
&lt;owl:disjointWith rdf:resource="#IndustrialBuilding"/&gt;
&lt;owl:disjointWith rdf:resource="#MilitaryBuilding"/&gt;
&lt;owl:disjointWith rdf:resource="#ReligiousBuilding"/&gt;
```

```
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<owl:Class rdf:ID="PhoneCharger">
 <rdfs:subClassOf rdf:resource="#StandBy"/>
 <owl:disjointWith rdf:resource="#BroadBand"/>
 <owl:disjointWith rdf:resource="#DeskTopComputer"/>
 <owl:disjointWith rdf:resource="#Television"/>
</owl:Class>
<owl:Class rdf:ID="PhotovoltaicComponent">
 <rdfs:subClassOf rdf:resource="#Component"/>
 <owl:disjointWith rdf:resource="#BalanceOfComponent"/>
</owl:Class>
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    <rdf:Description>
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      <rdf:Description rdf:about="#x"/>
     </swrl:argument1>
     <swrl:classPredicate rdf:resource="#PhotovoltaicComponent"/>
    </rdf:Description>
   </rdf:first>
   <rdf:rest>
    <swrl:AtomList>
     <rdf:first>
      <rdf:Description>
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       <swrl:argument2>
        <rdf:Description rdf:about="#e"/>
       </swrl:argument2>
       <swrl:argument1>
        <rdf:Description rdf:about="#x"/>
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   </rdf:rest>
  </swrl:AtomList>
 </swrl:body>
 <swrl:head>
  <swrl:AtomList>
   <rdf:first>
    <rdf:Description>
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     <swrl:arguments>
      <rdf:List>
       <rdf:first>
        <rdf:Description rdf:about="#x"/>
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         </rdf:first>
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```xml
        </rdf:rest>
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       <rdf:Description rdf:about="&sqwrl;select"/>
      </swrl:builtin>
     </rdf:Description>
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  </swrl:head>
 </swrl:Imp>
 <owl:Class rdf:ID="PhotovoltaicSystem">
  <rdfs:subClassOf rdf:resource="#Solar"/>
  <rdfs:subClassOf>
   <owl:Restriction>
    <owl:onProperty rdf:resource="#isComposedOf"/>
    <owl:someValuesFrom rdf:resource="#Component"/>
   </owl:Restriction>
  </rdfs:subClassOf>
  <owl:disjointWith rdf:resource="#SolarThermal"/>
 </owl:Class>
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      </swrl:argument1>
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    </rdf:first>
    <rdf:rest>
     <swrl:AtomList>
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       <rdf:Description>
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        <swrl:argument2>
         <rdf:Description rdf:about="#y"/>
        </swrl:argument2>
        <swrl:argument1>
         <rdf:Description rdf:about="#x"/>
        </swrl:argument1>
        <swrl:propertyPredicate rdf:resource="#isComposedOf"/>
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      </rdf:first>
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    </rdf:rest>
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  </swrl:body>
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```xml
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    </swrl:arguments>
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    </swrl:builtin>
   </rdf:Description>
  </rdf:first>
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      <rdf:Description rdf:about="#x"/>
     </swrl:argument1>
     <swrl:classPredicate rdf:resource="#PhotovoltaicSystem"/>
    </rdf:Description>
   </rdf:first>
   <rdf:rest>
    <swrl:AtomList>
     <rdf:first>
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       <swrl:argument2>
        <rdf:Description rdf:about="#y"/>
       </swrl:argument2>
       <swrl:argument1>
        <rdf:Description rdf:about="#x"/>
       </swrl:argument1>
       <swrl:propertyPredicate rdf:resource="#isSuppliedBy"/>
      </rdf:Description>
     </rdf:first>
     <rdf:rest>
      <swrl:AtomList>
       <rdf:first>
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         <rdf:type rdf:resource="&swrl;IndividualPropertyAtom"/>
         <swrl:argument2>
          <rdf:Description rdf:about="#z"/>
         </swrl:argument2>
         <swrl:argument1>
          <rdf:Description rdf:about="#x"/>
         </swrl:argument1>
         <swrl:propertyPredicate rdf:resource="#isComposedOf"/>
        </rdf:Description>
       </rdf:first>
       <rdf:rest rdf:resource="&rdf;nil"/>
      </swrl:AtomList>
     </rdf:rest>
    </swrl:AtomList>
   </rdf:rest>
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```
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  </swrl:body>
  <swrl:head>
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      <swrl:arguments>
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        </rdf:first>
        <rdf:rest>
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          <rdf:first>
           <rdf:Description rdf:about="#y"/>
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          <rdf:rest>
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            <rdf:first>
             <rdf:Description rdf:about="#z"/>
            </rdf:first>
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        </rdf:rest>
       </rdf:List>
      </swrl:arguments>
      <swrl:builtin>
       <rdf:Description rdf:about="&sqwrl;select"/>
      </swrl:builtin>
     </rdf:Description>
    </rdf:first>
    <rdf:rest rdf:resource="&rdf;nil"/>
   </swrl:AtomList>
  </swrl:head>
 </swrl:Imp>
 <PhotovoltaicSystem rdf:ID="PhotovoltaicSystem_2">
  <isComposedOf rdf:resource="#Module_13"/>
  <isResearchedBy rdf:resource="#Oxford_University"/>
  <isSuppliedBy rdf:resource="#Supplier_32"/>
  <isSuppliedBy rdf:resource="#Supplier_61"/>
 </PhotovoltaicSystem>
 <PhotovoltaicSystem rdf:ID="PhotovoltaicSystem_37"/>
 <PhotovoltaicSystem rdf:ID="PhotovoltaicSystem_38"/>
 <PhotovoltaicSystem rdf:ID="PhotovoltaicSystem_39"/>
 <PhotovoltaicSystem rdf:ID="PhotovoltaicSystem_40"/>
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<PhotovoltaicSystem rdf:ID="PhotovoltaicSystem_53"/>
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<PhotovoltaicSystem rdf:ID="PhotovoltaicSystem_71"/>
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<PhotovoltaicSystem rdf:ID="PhotovoltaicSystem_The_Solar_House">
 <isComposedOf rdf:resource="#Module_The_Oxford_Solar_House"/>
 <isResearchedBy rdf:resource="#Oxford_University"/>
</PhotovoltaicSystem>
<owl:Class rdf:ID="RainWaterHarvesting">
 <rdfs:subClassOf rdf:resource="#WaterConservation"/>
 <owl:disjointWith rdf:resource="#GreyWaterRecycling"/>
</owl:Class>
<owl:Class rdf:ID="RefrigeratorFreezer">
 <rdfs:subClassOf rdf:resource="#Cold"/>
 <owl:disjointWith rdf:resource="#Freezer"/>
</owl:Class>
<RefrigeratorFreezer rdf:ID="RefrigeratorFreezer_1">
 <hasPowerRating rdf:datatype="&xsd;float">0.2</hasPowerRating>
</RefrigeratorFreezer>
<owl:Class rdf:ID="ReligiousBuilding">
 <rdfs:subClassOf rdf:resource="#Building"/>
 <owl:disjointWith rdf:resource="#AgriculturalBuilding"/>
 <owl:disjointWith rdf:resource="#CommercialBuilding"/>
 <owl:disjointWith rdf:resource="#EducationalBuilding"/>
 <owl:disjointWith rdf:resource="#IndustrialBuilding"/>
 <owl:disjointWith rdf:resource="#MilitaryBuilding"/>
 <owl:disjointWith rdf:resource="#ParkingAndStorageBuilding"/>
 <owl:disjointWith rdf:resource="#ResidentialBuilding"/>
</owl:Class>
<owl:Class rdf:ID="RenewableEnergyTechnology">
 <rdfs:subClassOf rdf:resource="#BuildingConstructionTechnology"/>
 <owl:disjointWith rdf:resource="#BuildingConstructionElement"/>
 <owl:disjointWith rdf:resource="#BuildingConstructionMaterial"/>
 <owl:disjointWith rdf:resource="#ResourceEfficientTechnology"/>
</owl:Class>
<owl:Class rdf:ID="Research">
 <rdfs:subClassOf rdf:resource="#Organisation"/>
</owl:Class>
<owl:ObjectProperty rdf:ID="researchesOn">
 <rdfs:domain rdf:resource="#Research"/>
 <owl:inverseOf rdf:resource="#isResearchedBy"/>
 <rdfs:range>
  <owl:Class>
   <owl:unionOf rdf:parseType="Collection">
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```xml
      <owl:Class rdf:about="#Component"/>
      <owl:Class rdf:about="#RenewableEnergyTechnology"/>
     </owl:unionOf>
    </owl:Class>
   </rdfs:range>
   <rdfs:subPropertyOf rdf:resource="#involvesOrganisation"/>
  </owl:ObjectProperty>
  <owl:Class rdf:ID="ResidentialBuilding">
   <rdfs:subClassOf rdf:resource="#Building"/>
   <owl:disjointWith rdf:resource="#AgriculturalBuilding"/>
   <owl:disjointWith rdf:resource="#CommercialBuilding"/>
   <owl:disjointWith rdf:resource="#EducationalBuilding"/>
   <owl:disjointWith rdf:resource="#IndustrialBuilding"/>
   <owl:disjointWith rdf:resource="#MilitaryBuilding"/>
   <owl:disjointWith rdf:resource="#ParkingAndStorageBuilding"/>
   <owl:disjointWith rdf:resource="#ReligiousBuilding"/>
  </owl:Class>
  <ResidentialBuilding rdf:ID="ResidentialBuilding_106"/>
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  <ResidentialBuilding rdf:ID="ResidentialBuilding_140"/>
  <ResidentialBuilding rdf:ID="ResidentialBuilding_141"/>
  <ResidentialBuilding rdf:ID="ResidentialBuilding_The_Oxford_Solar_House">
   <hasContent rdf:resource="#GridConnected_3_Solar_House"/>
   <hasDailyPeakEnergyLoad rdf:datatype="&xsd;float">4.0</hasDailyPeakEnergyLoad>
   <hasLocation rdf:datatype="&xsd;string">Oxford</hasLocation>
   <rdfs:comment rdf:datatype="&xsd;string"
    >The Oxford solar house is the first house in the UK designed to maximise energy efficiency with a
fully integrated photovoltaic roof. The house was designed by Susan Roaf, a former Professor of Oxford
```

```
Brookes University, now a Professor at Heriot-Watt University. The house was built in 1995 and is
located in a suburban street in North Oxford. The Oxford solar house is a six bedroom family home. It
produces only 130 KgCO2/annum/m&#178;, in contrast to comparable UK houses that produce 5 000 Kg
CO2/annum/m&#178;.</rdfs:comment>
 </ResidentialBuilding>
 <owl:Class rdf:ID="ResourceEfficientTechnology">
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  <owl:disjointWith rdf:resource="#BuildingConstructionElement"/>
  <owl:disjointWith rdf:resource="#BuildingConstructionMaterial"/>
  <owl:disjointWith rdf:resource="#RenewableEnergyTechnology"/>
 </owl:Class>
 <Installer rdf:ID="Sharp"/>
 <owl:Class rdf:ID="SmartSystem">
  <rdfs:subClassOf rdf:resource="#ResourceEfficientTechnology"/>
  <owl:disjointWith rdf:resource="#WasteMinimisation"/>
  <owl:disjointWith rdf:resource="#WaterConservation"/>
 </owl:Class>
 <owl:Class rdf:ID="Solar">
  <rdfs:subClassOf rdf:resource="#RenewableEnergyTechnology"/>
  <owl:disjointWith rdf:resource="#Biomass"/>
  <owl:disjointWith rdf:resource="#Geothermal"/>
  <owl:disjointWith rdf:resource="#Hydro"/>
  <owl:disjointWith rdf:resource="#Tidal"/>
  <owl:disjointWith rdf:resource="#Wind"/>
 </owl:Class>
 <Installer rdf:ID="Solar_Century"/>
 <Array rdf:ID="Solar_House_Array">
  <isComposedOf rdf:resource="#Module_The_Oxford_Solar_House"/>
  <isSuppliedBy rdf:resource="#BP_Solar"/>
 </Array>
 <owl:Class rdf:ID="SolarThermal">
  <rdfs:subClassOf rdf:resource="#Solar"/>
  <owl:disjointWith rdf:resource="#PhotovoltaicSystem"/>
 </owl:Class>
 <owl:Class rdf:ID="StandAloneDC">
  <rdfs:subClassOf rdf:resource="#NonGridConnected"/>
 </owl:Class>
 <StandAloneDC rdf:ID="StandAloneDC_10">
  <isComponentOf rdf:resource="#Array_10"/>
  <isComposedOf rdf:resource="#Array_10"/>
 </StandAloneDC>
 <owl:Class rdf:ID="StandAloneDCAC">
  <rdfs:subClassOf rdf:resource="#NonGridConnected"/>
 </owl:Class>
 <owl:Class rdf:ID="StandBy">
  <rdfs:subClassOf rdf:resource="#HouseholdAppliance"/>
  <owl:disjointWith rdf:resource="#Brown"/>
  <owl:disjointWith rdf:resource="#Cold"/>
  <owl:disjointWith rdf:resource="#Continuous"/>
 </owl:Class>
 <owl:Class rdf:ID="SubArray">
  <rdfs:subClassOf rdf:resource="#PhotovoltaicComponent"/>
  <rdfs:subClassOf>
   <owl:Restriction>
    <owl:onProperty rdf:resource="#isComposedOf"/>
    <owl:someValuesFrom rdf:resource="#ModulePanel"/>
   </owl:Restriction>
  </rdfs:subClassOf>
  <owl:disjointWith rdf:resource="#Array"/>
  <owl:disjointWith rdf:resource="#ArraySubField"/>
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 <owl:disjointWith rdf:resource="#Module"/>
 <owl:disjointWith rdf:resource="#ModulePanel"/>
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 <rdfs:subClassOf rdf:resource="#Business"/>
</owl:Class>
<Supplier rdf:ID="Supplier_32">
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 <suppliesPhotovoltaicSystem rdf:resource="#PhotovoltaicSystem_2"/>
</Supplier>
<Supplier rdf:ID="Supplier_61">
 <suppliesPhotovoltaicSystem rdf:resource="#PhotovoltaicSystem_2"/>
</Supplier>
<Supplier rdf:ID="Supplier_62">
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 <suppliesPhotovoltaicSystem rdf:resource="#Inverter_1"/>
 <suppliesPhotovoltaicSystem rdf:resource="#Module_14"/>
</Supplier>
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 <rdfs:domain rdf:resource="#Supplier"/>
 <owl:inverseOf rdf:resource="#isSuppliedBy"/>
 <rdfs:range>
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    <owl:Class rdf:about="#Component"/>
    <owl:Class rdf:about="#RenewableEnergyTechnology"/>
   </owl:unionOf>
  </owl:Class>
 </rdfs:range>
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</owl:ObjectProperty>
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 <owl:disjointWith rdf:resource="#Building"/>
 <owl:disjointWith rdf:resource="#BuildingConstructionSystem"/>
 <owl:disjointWith rdf:resource="#BuildingConstructionTechnology"/>
 <owl:disjointWith rdf:resource="#Component"/>
 <owl:disjointWith rdf:resource="#HouseholdAppliance"/>
 <owl:disjointWith rdf:resource="#Organisation"/>
 <owl:disjointWith rdf:resource="#WorstModuleSupplier"/>
</rdf:Description>
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     <swrl:arguments>
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       <rdf:first>
        <rdf:Description rdf:about="#c"/>
       </rdf:first>
       <rdf:rest rdf:resource="&rdf;nil"/>
      </rdf:List>
     </swrl:arguments>
     <swrl:builtin>
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     </swrl:builtin>
    </rdf:Description>
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    <rdf:rest rdf:resource="&rdf;nil"/>
   </swrl:AtomList>
  </swrl:body>
  <swrl:head>
   <swrl:AtomList>
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     <rdf:Description>
      <rdf:type rdf:resource="&swrl;BuiltinAtom"/>
      <swrl:arguments>
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      </swrl:arguments>
      <swrl:builtin>
       <rdf:Description rdf:about="&sqwrl;select"/>
      </swrl:builtin>
     </rdf:Description>
    </rdf:first>
    <rdf:rest rdf:resource="&rdf;nil"/>
   </swrl:AtomList>
  </swrl:head>
 </swrl:Imp>
 <owl:Class rdf:ID="Television">
  <rdfs:subClassOf rdf:resource="#StandBy"/>
  <owl:disjointWith rdf:resource="#BroadBand"/>
  <owl:disjointWith rdf:resource="#DeskTopComputer"/>
  <owl:disjointWith rdf:resource="#PhoneCharger"/>
 </owl:Class>
 <Television rdf:ID="Television_2">
  <hasPowerRating rdf:datatype="&xsd;float">0.33</hasPowerRating>
 </Television>
 <owl:Class rdf:ID="Tidal">
  <rdfs:subClassOf rdf:resource="#RenewableEnergyTechnology"/>
  <owl:disjointWith rdf:resource="#Biomass"/>
  <owl:disjointWith rdf:resource="#Geothermal"/>
  <owl:disjointWith rdf:resource="#Hydro"/>
  <owl:disjointWith rdf:resource="#Solar"/>
  <owl:disjointWith rdf:resource="#Wind"/>
 </owl:Class>
 <owl:Class rdf:ID="TraditionalMethodsOfConstruction">
  <rdfs:subClassOf rdf:resource="#BuildingConstructionSystem"/>
  <owl:disjointWith rdf:resource="#ModernMethodsOfConstruction"/>
 </owl:Class>
 <owl:Class rdf:ID="WasteMinimisation">
  <rdfs:subClassOf rdf:resource="#ResourceEfficientTechnology"/>
  <owl:disjointWith rdf:resource="#SmartSystem"/>
  <owl:disjointWith rdf:resource="#WaterConservation"/>
 </owl:Class>
 <owl:Class rdf:ID="WaterConservation">
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  <owl:disjointWith rdf:resource="#SmartSystem"/>
  <owl:disjointWith rdf:resource="#WasteMinimisation"/>
 </owl:Class>
 <owl:Class rdf:ID="Wet">
  <rdfs:subClassOf rdf:resource="#Brown"/>
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```

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</owl:Class>
<owl:Class rdf:ID="Wind">
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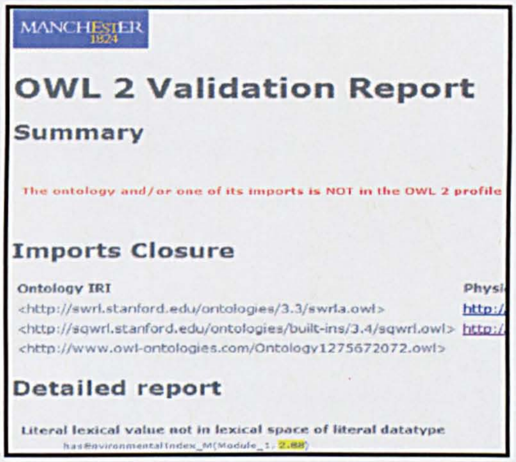
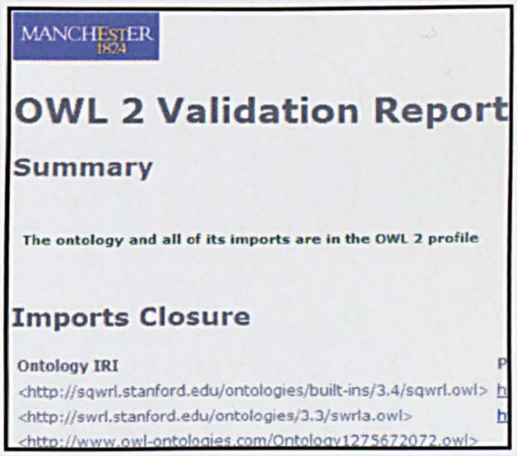
</owl:Class>
<owl:Class rdf:ID="WorstModuleSupplier">
 <owl:disjointWith rdf:resource="#BestModuleSupplier"/>
 <owl:disjointWith rdf:resource="#Building"/>
 <owl:disjointWith rdf:resource="#BuildingConstructionSystem"/>
 <owl:disjointWith rdf:resource="#BuildingConstructionTechnology"/>
 <owl:disjointWith rdf:resource="#Component"/>
 <owl:disjointWith rdf:resource="#HouseholdAppliance"/>
 <owl:disjointWith rdf:resource="#Organisation"/>
 <owl:disjointWith rdf:resource="&swrla;Entity"/>
</owl:Class>
<swrl:Imp rdf:ID="query-8.14">
 <swrl:body>
  <swrl:AtomList>
   <rdf:first>
    <rdf:Description>
     <rdf:type rdf:resource="&swrl;ClassAtom"/>
     <swrl:argument1>
      <rdf:Description rdf:about="#y"/>
     </swrl:argument1>
     <swrl:classPredicate rdf:resource="#WorstModuleSupplier"/>
    </rdf:Description>
   </rdf:first>
   <rdf:rest rdf:resource="&rdf;nil"/>
  </swrl:AtomList>
 </swrl:body>
 <swrl:head>
  <swrl:AtomList>
   <rdf:first>
    <rdf:Description>
     <rdf:type rdf:resource="&swrl;BuiltinAtom"/>
     <swrl:arguments>
      <rdf:List>
       <rdf:first>
        <rdf:Description rdf:about="#y"/>
       </rdf:first>
       <rdf:rest rdf:resource="&rdf;nil"/>
      </rdf:List>
     </swrl:arguments>
     <swrl:builtin>
      <rdf:Description rdf:about="&sqwrl;select"/>
     </swrl:builtin>
    </rdf:Description>
   </rdf:first>
   <rdf:rest rdf:resource="&rdf;nil"/>
  </swrl:AtomList>
 </swrl:head>
</swrl:Imp>
<swrl:Imp rdf:ID="query-8.15">
 <swrl:body>
  <swrl:AtomList>
   <rdf:first>
```

```
<rdf:Description>
 <rdf:type rdf:resource="&swrl;ClassAtom"/>
 <swrl:argument1>
  <rdf:Description rdf:about="#y"/>
 </swrl:argument1>
 <swrl:classPredicate rdf:resource="#WorstModuleSupplier"/>
</rdf:Description>
</rdf:first>
<rdf:rest>
 <swrl:AtomList>
  <rdf:first>
   <rdf:Description>
    <rdf:type rdf:resource="&swrl;DatavaluedPropertyAtom"/>
    <swrl:argument2>
     <rdf:Description rdf:about="#a"/>
    </swrl:argument2>
    <swrl:argument1>
     <rdf:Description rdf:about="#y"/>
    </swrl:argument1>
    <swrl:propertyPredicate rdf:resource="#hasLocation"/>
   </rdf:Description>
  </rdf:first>
  <rdf:rest rdf:resource="&rdf;nil"/>
 </swrl:AtomList>
</rdf:rest>
</swrl:AtomList>
</swrl:body>
<swrl:head>
 <swrl:AtomList>
  <rdf:first>
   <rdf:Description>
    <rdf:type rdf:resource="&swrl;BuiltinAtom"/>
    <swrl:arguments>
     <rdf:List>
      <rdf:first>
       <rdf:Description rdf:about="#y"/>
      </rdf:first>
      <rdf:rest>
       <rdf:List>
        <rdf:first>
         <rdf:Description rdf:about="#a"/>
        </rdf:first>
        <rdf:rest rdf:resource="&rdf;nil"/>
       </rdf:List>
      </rdf:rest>
     </rdf:List>
    </swrl:arguments>
    <swrl:builtin>
     <rdf:Description rdf:about="&sqwrl;select"/>
    </swrl:builtin>
   </rdf:Description>
  </rdf:first>
  <rdf:rest rdf:resource="&rdf;nil"/>
 </swrl:AtomList>
</swrl:head>
</swrl:Imp>
</rdf:RDF>
```

Appendix 8.1. Verification for OWL compliance





Appendix 9.1. List of publications

A: Journal publications

1. J.H.M Tah and **F.H. Abanda** (2011) Sustainable building technology knowledge representation: Using Semantic Web techniques. *Journal of Advanced Engineering Informatics,* Vol. 25 (3), pp. 547-558.

2. **Henry Abanda**, Austine Ng'ombe, Joseph H. M. Tah and Ramin Keivani (2011) An ontology-driven decision support system for land delivery in Zambia. *Expert Systems with Applications,* Vol 38 (9), pp. 10896 -10905.

3. **Fonbeyin H. Abanda,** J.H.M Tah, C. Pettang and M. Manjia (2011) An ontology-driven house-building labour cost estimation in Cameroon. *Journal of Information Technology in Construction*, Vol. 16, pp. 617-634.

4. Pettang, C., Manjia, M.B. and **Abanda, F.H.** (in press) Urban Self-Building Labour Cost Modelling in Cameroon. *Journal of Construction in Developing Countries.*

5. Abanda, F.H., Tah, J.H.M. and Duce, D. (submitted) PV-TONS: A ***P***hotovoltaic ***T***echnology ***ON***tology ***S***ystem for the design of PV-systems. *Journal of Information Sciences.*

B: Book chapter

6. Argüello, M., Abusa, M.M, Fernandez, M.J., Brookes, V. and **Abanda, F.H.** (2007) A Web services-based annotation application for semantic annotation of highly specialised documents about the field of Marketing. Lecture Notes in Computer Science, Volume 4803/2007, pp.1135-1152.

C: Research project

7. Keivani, R. Joseph H. M. Tah, Esra Kurul and **F.H. Abanda** (2010) Green Jobs Creation Through Sustainable Refurbishment in the Developing Countries, Working Paper No. 275, International Labour Office, Geneva.

D: Peer-reviewed conference papers

8. **Abanda, H.**, Tah, J.H.M., Cheung, F. and Zhou, W. (2010) Measuring the Embodied Energy, Waste and CO_2 Emissions from Construction Activity: An Overview. *In*: The Proceedings of the International Conference on Computing in Civil and Building Engineering 2010, June 30-July 2, The University of Nottingham, UK, pp. 361-366.

9. Tah, J.H.M., Zhou, W., **Abanda, F.H.** and Cheung, F.K.T (2010) Towards a holistic modelling framework for embodied carbon and waste in the building lifecycle. *In*: The Proceedings of the International Conference on Computing in Civil and Building Engineering 2010, June 30-July 2, The University of Nottingham, UK, pp. 82-87.

10. **Abanda, H.,** J.H.M. Tah, Chrispin Pettang, Manjia, M.B. and Sambo, K. (2010) An ontology-driven approach to labour cost estimation: The case of house-building projects in Cameroon. *In:* The Proceedings of the International Conference on Computing in Civil and Building Engineering 2010, June 30-July 2, The University of Nottingham, UK, pp. 225-231.

11. **Abanda, F.H.**, Tah, J., Kurul, E. and Duce, D. (2009) Exploring the use of protégé in representing knowledge on sustainable building technologies. *In*: Ahmed, V. *et al.* (Ed) Procs 9th International Postgraduate Research Conference (IPGRC), 29-30th 2009, The Lowry, Salford Quays, Greater Manchester, UK, pp. 449-460.

12. Tah, J.H.M. and **Abanda, F.H.** (2009) Exploring the use of Semantic Web techniques for representing knowledge about sustainable building technologies. *In*:The Proceedings of the Fifth International Conference on Construction in the 21st Century (CITC-V) "Collaboration and Integration in Engineering, Management and Technology" May 20-22, 2009, Istanbul, Turkey.

13. **Abanda, F.H.** (2009) Sustainable building technology ontology. *In*: The Proceedings of the 11th International Protégé Conference, June 23-26, 2009 - Netherlands, pp.15.

14. **Abanda, F.H.** and Tah, H.M. (2008) Sustainable building technology ontology. *In*: Dainty, A(Ed) Procs 24th Annual ARCOM Conference, 1-3 September 2008, Cardiff, UK, Association of Researchers in Construction Management, pp. 677-686.

15. **Abanda, F.H.** and Tah, H.M. (2007) Towards the Development of a Knowledge-Repository of Emerging Innovations for Sustainable Housing Development, *In*: Proceedings of the 6th International Postgraduate Research Conference, University of Salford, pp. 345-353.

16. Charly, Y., Tonye, E. and **Abanda, F.H.** (2010) Vers la mise en œuvre d'un outil d'aide de la maitrise du trait de côte littoral camerounaise. *In*: The Proceedings of the International Conference on ICT for Africa 2010, March 25-28th, Yaounde, Cameroon, pp. 224-229.

17. Manjia, M.B., Pettang, C. and **Abanda, F.H.** (2010) L'approche matricielle pour l'estimation du cout de la main d'œuvre dans le chantier de construction camerounais. *In*: The Proceedings of the International Conference on ICT for Africa 2010, March 25-28th, Yaounde, Cameroon, pp.190-198.