BIM-Based Smart Compliance Checking to Enhance Environmental Sustainability

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Abstract

The construction industry has been facing immense challenges to move towards more- sustainable buildings with minimum harm to the environment. The building design and construction process is conditioned by numerous sustainability regulations and assessment measures, to promote sustainable construction.

These regulations are continuously expanding in their requirements, and incorporating a huge amount of data that needs to be rigorously dealt with, in order to check compliance and asses the performance

Building Information Modelling (BIM) promotes the effective information and process integration across the building life-cycle and supply chain. This integration should comply with an increasingly-complex regulatory environment and statutory requirements.

The aim of this thesis is to improve and facilitate the sustainability compliance checking process, by focusing on inter-operability between existing methods of compliance checking and building information modelling. This thesis presents a generic approach for BIM based compliance checking against standards and regulations, with a particular focus on sustainable design and procurement.

To achieve this, a methodology has been developed to enable automated sustainability compliance checking. This involves (a) extracting regulatory requirements from sustainability-related regulations available in textual format; (b) converting these into BIM- compatible rules; (c) processing these rules through a dedicated rule-based service; and (d) performing regulatory compliance analysis underpinned by the concept of BIM. A semantic extension of the IFC (Industrial Foundation Classes) for sustainability compliance checking has been developed. The outcome of the research was implemented in the RegBIM project and is in the process of being exploited as an online service by industrial organization, the Building Research Establishment (BRE) in the UK.

List of Publications

- T KASIM, H. J. L., Y REZGUI 2012. BREEAM Based Dynamic Sustainable Building Design Assessment. EG-ICE International Workshop on Intelligent Computing in Engineering Herrsching (Munich), Germany
- T KASIM, H. J. L., Y REZGUI, T BEACH 2013a. Automated Sustainability Compliance Checking Process. EG-ICE International Workshop on Intelligent Computing in Engineering Vienna, Austria.
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- Proof Of Concept. CONVR 2013, 13th International Conference in Construction Applications of Virtual Reality. London, United Kingdom (Awarded as the best PhD research paper)
- T KASIM, H. L., TH BEACH, YR REZGUI. BIM based Regulatory Compliance Checking: A BREEAM Application. Advanced Engineering Informatics.- (Pending).
- T. KASIM, H. J. L., Y. REZGUI, T.BEACH, SHANGJIE HOU 2014. A comparative study between traditional sustainability assessment methods, rules based automated approach and the application of engineering Ontologies. EG-ICE International Workshop on Intelligent Computing in Engineering 2014. Cardiff, United Kingdom.
- T BEACH , T. K., H J LI, Y REZGUI, 2013. Towards Automated Compliance Checking in the Construction Industry. DEXA 2013, 24th International Conference on Database and Expert Systems Applications. Prague, Czech Republic.
- TH BEACH, Y. R., H LI, T KASIM 2015. A Rule-based Semantic Approach for Automated Regulatory Compliance in the Construction Sector. Expert Systems with Applications.

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LIST OF SYMBOLS AND ABBREVIATIONS

The following symbols and abbreviations have been used in this thesis:

API	Application Programming Interface
BIM	Building Information Modelling
BPS	Building Performance Simulation
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Method
bSI	buildingSMART International
CASBEE	Comprehensive Assessment System for BuiltEnvironment
COBie	Construction Operations Building information exchange
CSH	Code for Sustainable Homes
DXF	Drawing eXchange Format
EPBD	European Performance of Buildings Directive
GBS	Green Building Studio
gbXML	Green Building eXtensible Markup Language
HK-BEAM	Hong Kong Building Environmental Assessment Method
IAI	International Alliance for Interoperability
IDM	Information Delivery Manual
IES<VE>	Integrated Environmental Solutions <VirtualEnvironment>
IFC	Industry Foundation Classes
IFD	International Framework for Dictionaries
IGES	Initial Graphics Exchange Specification
ISO	International Standards Organisation
JaGBC	Japanese GreenBuild Council
KBSI	Knowledge Based Systems Inc.
LZCT	Low and Zero Carbon Technologies
NIBS	National Institute of Building Sciences
OmniClass	OmniClass Construction Classification System
RIBA	Royal Institute of British Architects
SAP	Standard Assessment Procedure
SBEM	Simplified Building Energy Model

SPF	STEP based Physical File
STEP	Standard for the Exchange of Product Model Data
USGBC	United States Green Building Council
WBCSD	World Business Council for Sustainable Development
XML	eXtensible Markup Language
XSD	XML Schema Definition
U	U-Value
MVD	Model View definition
OWL	The web ontology language
Protégé	Open-source ontology editor

Chapter 1

Introduction

1.0 Introduction

Current practice within the construction industry demands more effective tools to design sustainable and high-performance buildings that are able to achieve low carbon footprints (Everett et al., 2012). To achieve this, professionals throughout the construction industry are increasingly required to use environmental assessment systems to evaluate building performance during the design, construction and operation stages (Singh et al., 2009). Several frameworks are currently available to provide environmental assessments e.g., BREEAM, LEED, etc. (Trusty, 2000), but there is still a lack of highly-efficient and convenient tools that can be used to manage the overall assessment process using these schemes (Thérivel and Paridario, 2013). This lack of tools has raised several important issues that need to be considered while assessing the sustainability performance of buildings; these include large amounts of assessment data that needs to be collected, in addition to data on the nature and the number of the performance criteria and their divergent influence on the different stages of construction projects (Jaffe et al., 2005). The current manual practice of conducting environmental assessment at the later stages of the construction process is not effective, since any improvements required to achieve the desired sustainable performance prove to be costly and time consuming (Kibert, 2008). The construction industry needs a fundamental change in the assessment culture and methodology in order to provide the opportunity to gain a holist overview of the overall life cycle of building performance in an integrated way (Lee and George, 2013).

The introduction of Building Information Modelling (BIM) has presented a unique opportunity to optimise the sustainability performance of buildings. In 2011, the UK government announced that the use of BIM will be mandatory for all public sector projects from 2016 (Counsell, 2012). To this end, Bentley BIM Solutions have been the first company to introduce a BIM-based regulatory compliance framework: the AECOsim Compliance Manager (Volkov et al., 2013). Although the AECOSim compliance manager and similar BIM tools streamline a Buildings' sustainability compliance checking process, the existing tools are not able to provide an integrated solution by embedding the regulatory requirements within the software environment, and intelligently extracting the necessary data automatically from the BIM model for compliance checking.

The approach presented in this thesis will address the challenge of automating the highly-complex and technically-rigorous regulation assessment process. The availability of such a system will prove invaluable in increasing the functionality of BIM solutions to allow building designers to manage the sustainability performance of their design during the early stages of a construction project. In addition, such a solution will have the significant advantages of reducing the time required for the assessment process, and conducting the work at a minimum cost.

1.1 Problem Description

1.1.1 Sustainability assessment and compliance

The construction industry began to recognise the impact of its activities on the environment during the 1990s. During that time, the industry faced immense challenges in shifting from green building to sustainable building, with different methods being developed to evaluate the 'greenness' of buildings (Kibert, 2008). The benefits of using environmental assessment methods vary from very detailed life cycle assessment methods (*LCA*) to higher-level impact assessment methods (Environmental Impact Assessment, IEA) (Barrow, 1997).

The methodologies used to check a building's compliance with sustainability regulations are highly-complex, rigorous and costly. These methods have large data requirements at every stage of checking, and this makes it difficult to conduct sustainability assessment and compliance checking continuously and accurately (Cole, 2005). In particular, when the assessment is considered at a later stage, it greatly reduces the impact that these regulations can potentially have on a project, and may result in the desired sustainability rating being unobtainable, or only being obtainable by incurring large additional costs.

1.1.2 BIM and the building design process

With the increasing complexity of modern buildings and the growing amount of information generated over a building's life cycle, the importance of Building Information Modelling (BIM) is growing rapidly (Yan and Damian, 2008). Over the past 100 years, the designs of buildings and construction practices have changed dramatically; buildings have become more sophisticated and possess increasingly-complex inter-related systems (Krygiel and Nies, 2008). With this added complexity, further roles and responsibilities have been created, and all building stakeholders, throughout the building lifecycle, have had to adapt to these changes. The increases in building specialisation and complexity have demanded more time, cost and effort, in order to coordinate all of the activities involved, and to manage the process and life cycle of a construction project (Katranuschkov et al., 2010a); the evolution of BIM technologies offers a promising method to tackle these difficulties.

Utilising BIM methodology within a construction project requires an advanced approach to information sharing and communication amongst all of the stakeholders in the project. A BIM methodology can also enhance the project management process by introducing a 3D simulation of the building and its components. These simulations step beyond demonstrating different options of a buildings' design; they show environmental variables according to these design options, identify changes in the quantities of materials, visualise sustainability performance, and also predict collisions in design aspects (Manke et al.). A real-time demonstration of the building's performance enhances the accuracy and the efficiency of BIM-complaint buildings.

1.1.3 The role of BIM for compliance checking

The relatively recent emergence of BIM technologies provides a key opportunity to optimise the process of environmental assessment and regulatory compliance checking. A large volume of published studies and existing research indicates that BIM can streamline the sustainability compliance checking process throughout the life cycle of a construction project (Gray and Bebbington, 2001, Azhar et al., 2010, Nguyen et al., 2010, Everett et al., 2012). It is anticipated that when BIM tools are integrated with sustainability measuring tools, in order to design high performance buildings, significant efficiency improvements can be achieved.

The uptake of BIM tools is supported by Autodesk, indicating that they believe that BIM makes an efficient contribution to achieving sustainable construction by "making the information required for sustainable design, analysis and certification routinely available simply as a by-product of the standard design process" (Azhar et al., 2009). Although a number of studies have been conducted relating to incorporating collaborative BIM design into a construction project, there is little known about the integration of sustainable performance analysis into these processes. Several attempts have been made to integrate data about the performance of buildings from building simulation tools into BIM environments to achieve an optimised sustainable design (Welle et al., 2011). However, the practical implementations of these trials manifest some technical barriers to achieving the desired goals, such as problems related to the data exchange between different software tools.

The construction industries' adoption of BIM provides the opportunity to realise numerous benefits throughout the project conception, design, construction and post-occupancy phases of a building facility. In the specific context of sustainability analysis, linking the building information model to performance analysis tools allows for the evaluation of the performance during the early design phases. This is not currently possible using existing tools, which require that a separate performance simulation be performed at the end of the design process, thus reducing the opportunities for early modifications that could improve the building's overall performance

1.2 Case study

The author was interested in a number of BREEAM assessment studies of existing buildings and new-builds during the course of this thesis, this was conducted in conjunction with certified BREEAM assessors from the Building Research Establishment (BRE). The assessment process has been a motivational case study for the thesis; it provides evidence that sustainability compliance checking is currently a tedious, time consuming and expensive process due to the complexity of the relevant regulations, and the fragmented information of the construction project which needs to be gathered prior to the assessment. The evolution of BIM technologies can streamline the assessment process by providing the relevant information in a digital format ready to be checked against targeted regulations. Currently, there is a lack of interoperability between BIM tools and regulations; several aspects need to be considered to achieve a promising level of interoperability to facilitate compliance checking.

1.2.1 BREEAM Assessment Process

BREEAM is the environmental assessment framework adopted in the UK. (Global, 2008). With similarity to other environmental assessment methods described in Chapter 2 of this thesis, the basis of the BREEAM scheme is to grade the individual building according to its environmental performance. The process involves the quantification of the environmental impact of design features as numerical expressions of credit; these credits, added together, represent the performance of the building.

There are numerous building aspects which can be considered directly during the modeling phase, in order to improve the building's performance. Taking the ENE Issue (Energy performance of the building) of BREEAM as an example, as illustrated in Figures 1-1, 1-2 and Table 1-1, there are many aspects related to energy performance which can be directly obtained through the BIM model (Autodesk Revit or Bentley BIM models), such as the orientation of the building, the design or layout of the windows, or the insulation specifications; these aspects affect the BREEAM rating significantly. With the possibility of visualizing the building performance in the modeling phase, designers will be able to achieve the desired rating with minimal effort and investment.

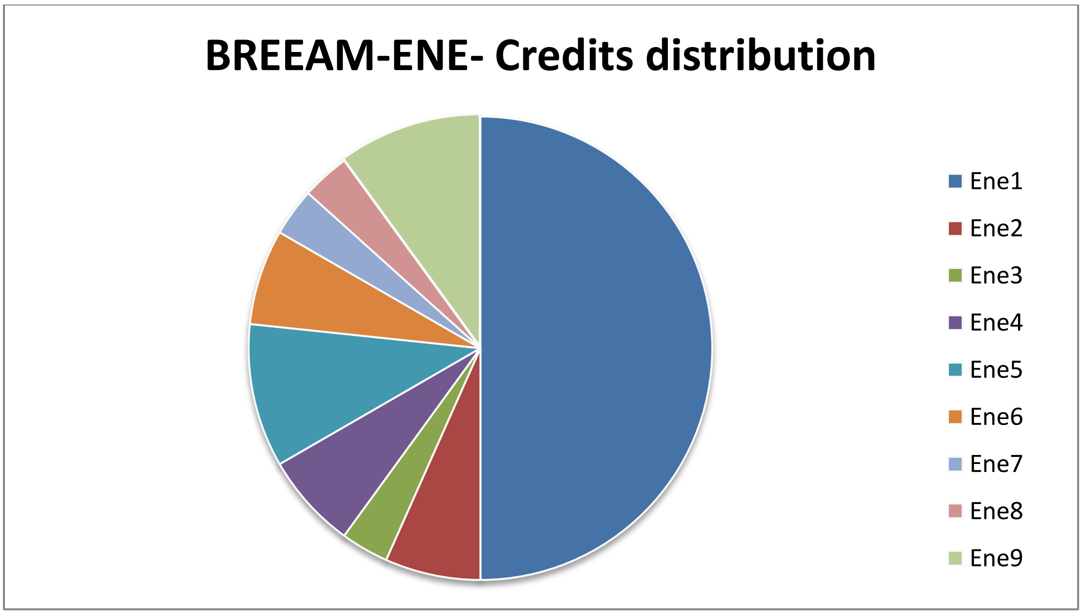

Figure 1-1 Ene BREEAM Credits distribution

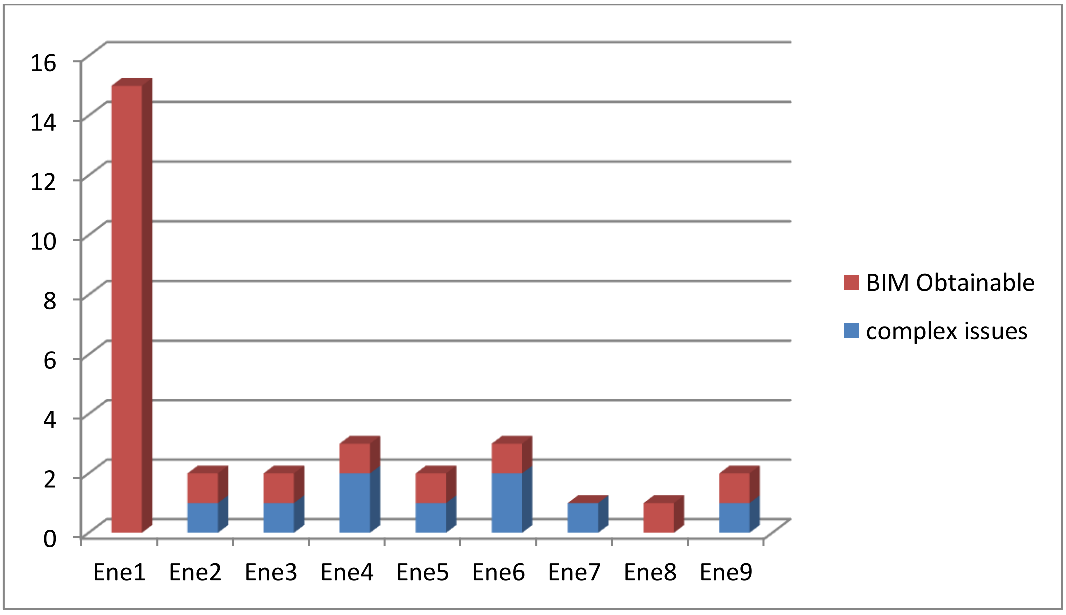

Figure 1-2 Ene The impact of BIM on BREEAM Credits

Table 1-1 The impact of BIM for performance enhancement of Ene

Issue ID	**Issue Description**	**Available credits**	**BIM obtainable**
Ene 1	Reduction of CO2 emissions	15	15
Ene 2	Energy monitoring	2	1
Ene 3	External lighting	1	1
Ene 4	Low and zero carbon technologies	5	4
Ene 5	Energy efficient cold storage	2	1
Ene 6	Energy efficient transportation system	3	2
Ene 7	Energy efficiency laboratory system	1	0
Ene 8	Energy efficient equipment	2	2
Ene 9	Dry space	1	0
Total		**32**	**26 80% of total Number of credits**

- ***Ene 1 Reduction of emissions***

The assessment of this issue is carried out by conducting some numerical calculations to determine the energy performance rating (EPR) of the building. The resulting EPR is compared with a benchmark, and then the corresponding BREEAM credits can be awarded; the process is further described in Chapter 4 of this thesis. Since the EPR of a building is relevant to its design features which can be demonstrated by the BIM model, all of the potential credits awarded for this sub-issue can be evaluated directly during the modelling phases.

- ***Ene 2 Energy monitoring***

The assessment of this sub-issue relies on the features of the energy monitoring system. Although one credit can only be awarded according to certain criteria of the energy management system, one BREEAM credit can be awarded if sub-meters for the energy supply are provided to every functional area or department within the building or a unit. The BIM model can obviously present the availability of these sub-meters. This is another ‘quick win’ BREEAM credit, which can be obtained directly during the modelling phase.

- ***Ene 3 External lighting***

A BREEAM credit can be awarded if there is external lighting provided within the construction zone of the building. The specification of the lighting needs to meet the requirements of energy efficiency and be controlled in a sustainable manner. The availability of external lighting is reliant on the existence of a ‘lighting’ object on the exterior part of the building. Also, the properties of ‘lighting’ are presented in the BIM model, so it is possible to evaluate whether the credit can be awarded or not according to the BIM data.

- ***Ene 4 Low and zero carbon technologies***

Up to four BREEAM credits can be awarded to the building when low or zero-carbon (LZC) energy sources are used in the building. The percentage of carbon reduction from these LZC sources compared to traditional energy sources is calculated via approved energy modelling software. The evaluation of this sub-issue can be carried out using the BIM model, according to the BIM data provided about the energy source, with the aid of energy modelling software.

- ***Ene 5 Energy efficient cold storage***

The assessment of this sub-issue is subject to the properties of the ‘refrigeration system’, in terms of energy efficiency and the reduction of carbon emissions. One of two credits can be awarded to the building if the refrigeration system is labelled as energy efficient. This information can be provided by the BIM model, since the properties of each object are described. However, this information is difficult to obtain if the refrigeration system demonstrates savings in indirect CO_2 emissions and complies with a relevant regulatory code. Therefore only one credit award can be obtained as a quick win, according to the BIM data.

- ***Ene 6 Energy efficient transportation system***

Up to two credits can be awarded if the building demonstrates energy efficient transportation appliances such as lifts, vehicles, escalators, moving walkway systems, etc. The specification of these systems can be described in the BIM model, and therefore the number of awarded credits is subject to the information provided.

- ***Ene 7 Energy efficiency laboratory system***

It can be difficult to assess the efficiency of laboratory systems because of the breadth of the assessment requirements of this particular issue. The laboratory system comprises multiple objects which all need to comply with the relevant standards. For example; ‘fume cupboards’ need to be compliant with the CIBES guide requirements, and the BIM model cannot necessarily provide all of the relevant information.

- ***Ene 8 Energy efficient equipment***

This issue deals with the functions and equipment which will be responsible for the significant majority of the energy consumption within the assessed buildings. A building with energy efficiency labelled equipment can be awarded two BREEAM credits, depending on the equipment’s properties.

The building equipment properties can be found in the BIM model, and therefore this issue can be assessed directly.

- ***Ene 9 Dry space***

It can be difficult to calculate the length of the internal and external drying line on the BIM model directly. Some calculations need to be carried out to assess this particular issue.

1.2.2 Discussion

This example highlights the fact that, by adopting BIM technologies, 80% of the BREEAM-ENE issued can be assessed based on the virtual BIM data with the benchmarks of the BREEAM rating system. In this case, if the BIM modeling concept is used during the early stages of design, design teams will be able to manipulate and modify their work to achieve the desired performance. In adopting modern BIM technologies accompanied by some technical improvements, designers can perform parametric studies to analyse and visualise building performance, and to perform a detailed and precise building simulation as well as an energy performance analysis. However, in order to feasibly conduct these analyses in the early design and pre-construction stages, comprehensive yet accessible sets of information and knowledge regarding building form are needed.

The BIM stores the entire building information data set in an integrated parametric database, which can be used to perform the analysis of many aspects of the design process. However, the full benefit of integrating the BIM with sustainability assessment systems needs to be critically investigated; in particular, some technical barriers need to be addressed related to the data exchange within the BIM environment, which sometimes limits the exploitation of BIM technologies. The information required to support the environmental assessment process is currently fragmented across domains, and not ready to be used as guidance to a designer or be accessible within a software-based design environment. Although the previously-mentioned motivation case study example focuses on the issue of energy, the majority of the sustainability aspects can be analysed continuously in the modeling phase. Furthermore, there is the potential that the real-time performance can be dynamically monitored as the design proceeds. It can be concluded that there is an urgent need for a methodology to enable dynamic requirement checking as a team designs their building. This issue will be addressed in the rest of this thesis.

1.3 Hypothesis, Aims and Objectives

The hypothesis of this thesis is that current BIM technologies can be enhanced to enable a sophisticated analysis of the sustainability performance of a buildings' design in a dynamic way to allow for increasingly efficient automatic regulatory compliance checking.

The aims of current research are listed below:

- To develop a new software system that streamlines the environmental assessment process embedded on BIM.
- To implement a software system that is capable to investigate the BIM model and to seek for regulatory compliance criteria.
- To intelligently assess buildings for regulatory compliance dynamically as the construction project proceed, and to modify the design continuously until it meet the desired performance.

The concrete objectives are:

- To identify current deficiency of BIM to support environmental assessment methods and rating systems
- To identify the missing data within the BIM model for certain requirement and to develop a methodology for obtaining a domain-compliant IFC.
- To convert text-formatted regulations into machine understandable coded rules.
- To use a rule engine and Ontology reasoner to inspect BIM model and to check compliance with sustainability requirements as benchmarked in BREEAM.
- To present a valid, efficient, accurate and scalable system with visualized, user- friendly interface to manage sustainability performance of buildings.

1.4 Research Questions

The current research aims to answer the following research questions:

Question 1(RQ1): How can the compliance requirements be identified smartly, with the increasing volume of criteria within the rapidly developing regulations?

- By utilising a methodology based upon a decision logic approach to analyse the targeted regulations and to categorise the assessment requirements according to the methods of assessment. This is further described in section (4.4.2).
- By converting the compliance criteria into complied coded rules. The rules are viable to conform to the continuous development of regulations. Further details are given in section (4.4.3)

Question 2(RQ2): How can the required data be extracted from a variety of data storage media, i.e. an IFC model?

- By disclosing the missing data within the IFC, and identifying additional sets of properties to establish a domain-compliant IFC. This is further described in section (4.4.3)
- By using a rules-based approach to explicitly map regulatory-compliance requirements to the domain-compliant IFC. Section (4.4.4) provides a detailed description.
- By defining a road-map for using engineering ontologies to extract implicit data from the IFC using reasoning. The details are given in Chapter 8.

Question 3(RQ3): How is it possible to dynamically manage and assess the performance of the building according to a targeted regulation?

- By automatically extracting and examining compliant data from the BIM model using a rule engine, described in section 4.4.5

Question 4(RQ4): How can the developed system be used to support automated sustainability compliance checking effectively?

- By validating the system implementation using a qualitative approach and comparing the traditional assessment process with the automated approach in real case studies. This is further described in chapter 7

1.5 Thesis Outline

The rest of the thesis is organised as follows. Chapter 2 introduces environmental assessment methods and rating systems in the construction industry. Different approaches, frameworks and methodologies for environmental assessment are briefly discussed in this chapter with a focus on the BREEAM assessment method. Environmental performance standards and regulations are also described in Chapter 2, and finally it summarises various tools for sustainability performance analysis.

Chapter 3 focuses on information management in the construction industry and the evolution of BIM technologies. In this chapter, a description of the adoption of BIM, its benefits and limitations are given, followed by a summary overview of some existing BIM tools and their usability. This chapter also describes the current collaboration and interoperability state of BIM. In addition, BIM technologies and information sharing are described, with a critical overview of the IFC data schema. Chapter 3 also brings together environmental sustainability compliance requirements and BIM interoperability to describe the existing work in the field of regulatory compliance checking, with a focus on sustainability-related issues in the AEC sector. Finally, the current principles methodologies, platforms and available solutions are critically summarised. Chapter 4 discusses the research methodology used to determine the research questions. In this chapter, different types of research methodologies are discussed, and the approach used justified in comparison with other approaches. Chapter 5 presents the core of the thesis; it outlines the developed methodology, giving a general overview of the system, and describes the details of the automatic sustainability compliance checking system that has been developed. Chapter 6 describes the process of integrating the developed system into the BIM environment. In this chapter, the semantic expansion of IFC to address BREEAM requirements is explained in detail. The details of how the rule engine executes and processes the predefined rules for compliance requirements are also described, since the rules-based approach for automating sustainability compliance checking has some limitations when compliance requirements are implicit within an IFC database.

Chapter 7 focuses on the implementation and validation of the system. The chapter presents case studies for the traditional sustainability assessment process of buildings, as compared with deploying the automated approach to conducting the assessment. Challenges and drawbacks are justified, while the advantages of the system implementation are reported. The chapter also investigates the usability of the system, and describes the efficiency saving deemed possible by its implementation.

Chapter 8 describes the role of engineering ontologies in using reasoning for extracting regulatory compliance requirements from the IFC. The chapter ends by concluding the merits and drawbacks of the approaches used.

Chapter 9 investigated the potential for developing MVD for sustainability compliance requirements. The chapter describes MVD development process

The final chapter of the thesis concludes all of the previously-mentioned aspects. The research outcome is discussed, and recommendations for further work are given.

Chapter 2

Environmental Assessment Methods and Rating Systems in Construction Sector

This chapter reviews the sustainability assessment methods and rating systems currently available in the construction industry. A general review of environmental performance standards and regulations is introduced in (Section 2.2) of this chapter, and environmental assessment methods and rating systems are described in (section 2.3). Different approaches, frameworks and methodologies for environmental assessment are briefly discussed in this section, with a focus on the BREEAM assessment method. Finally, various tools for sustainability performance analysis are summarized in (section 2.4).

2.0 Introduction

Achieving “Sustainability” in construction has become a central source of concern in recent years (Peattie, 2001). Environmental, social and economic factors are the primary aspects of sustainability, and the pillars of any society whose ultimate role is to achieve well-being for humankind of both current and future generations (Chang et al., 2011). The World Commission on Environment and Development (1987) identified sustainable development as ‘… development that meets the needs of the present without compromising the ability of future generations to meet their own needs’ (Brundtland, 1987). Sustainable development is a vast topic, and includes multi-disciplinary capacities and interpretations. It is evident that the construction industry is the field most accused of causing problems relating to the environment (Krygiel and Nies, 2008).

The impact of construction activities on the environment varies from excessive depletion of natural resources to the pollution caused by greenhouse gas emissions - the main contributor to global warming and climate change. In the UK, around 52% of CO_2 emissions come from creating or using buildings (Ürge-Vorsatz and Novikova, 2008); these figures indicate the need for urgent action to fundamentally improve buildings and constructions. During recent decades, intensive research studies have been conducted to develop methods and techniques to tackle environmental problems caused by the construction industry.

There exists a broad range of characteristics and activities which buildings may exhibit to demonstrate a degree of sustainability. For example, the use of construction materials is one of these important issues. Some researchers have focused on the sustainability of construction materials and the possibility of recycling and eco-labelling of building materials (Halliday, 2008, Anink et al., 1996) (Provis et al., 2010). Others have investigated the possible use of construction materials produced from waste or by-products from industrial recourses to minimize the impact of waste on the environment (Chateau, 2007). Another major source of concern is the energy consumption and CO_2 emissions during construction and buildings operation. A large and growing body of literature has investigated different methods and techniques to design energy-efficient buildings (Chwieduk, 2003). In addition, methods for water conservation and sustainable management systems have also been *widely investigated* in numerous research studies (Edwards and Turrent, 2013).

Apparently, tackling environmental issues in a comprehensive manner remains complex and problematic; as a result, sustainability experts have pointed to the implementation of effective and holistic environmental assessment methods and rating systems as a matter of urgency*.* Methods have proven their efficiency in mitigating the impact of construction projects on energy consumption, the environment and society in general (Fowler and Rauch, 2006a). Furthermore, several attempts have been made to embed environmental assessment processes within the life cycle of construction projects. (Virginia Cinquemani, 2010)) has published a guide for achieving higher BREEAM and Code for Sustainable Homes scores through the incorporation of assessment processes with the RIBA Outline Plan of Work and other procurement routes. A year later, a multi-disciplinary panel of architects and engineers with particular expertise in sustainable construction, assembled under the direction of the *Royal Institute of British Architects*' (RIBA's) Practice and Profession Committee, released the *Green Overlay to the RIBA Plan of Work* (Gething, 2011); the purpose of the guide is explicitly state how the environmental assessment tasks can be incorporated at every step in the design process. (Hartman, 2012)

The establishment of a mechanism and an agenda for the implementation of sustainable construction processes has been the subject of concerted effort in construction sector. However, best practices for sustainable construction continue to be the topic of interest of researchers and professionals across the world (Cole, 1998, Christmann, 2000, Porter and Kramer, 2006, Pitt et al., 2009). Researchers continue to investigate different methods and strategies for implementing policies to achieve the desired degree of sustainability for the construction phase.

Furthermore, a considerable amount of effort has been made to integrate sustainability assessment methods into the design process over the last few years (Gibson, 2006); building performance simulation is, however, not yet fully integrated. There remains no comprehensive and structured process to assist professionals in conducting building performance analysis, and to detect the “non-sustainable” features of the buildings from early stages of design. In recent years, there have been an increasing number of studies aiming to harness efficient building simulation technologies as design-decision support tools; these are intended to achieve optimum results in building performance, and to demonstrate compliance with sustainability regulations.

Two of the most common performance-based building regulations in the UK are the Code For Sustainable Homes (CSH) (Government, 2010), and BREEAM (BRE Environmental Assessment Method (Global, 2011b); the regulations are often stipulated by clients when purchasing buildings. Both of these regulations are termed “balanced scorecard methodologies”, meaning that each section of the regulations awards a fixed number of points (also called credits), and the credit total is used to provide an overall rating for each building.

Compliance with a sustainability rating system is not mandatory, although it is increasingly becoming a goal that many designers and authorities wish to achieve (Biswas et al., 2008). Unlike building codes, compliance to a specific rating system is a way to show that certain measures have been taken to ensure the mandates of sustainability in the building domain.

2.1 Environmental performance standards and regulations

2.1.1 Building regulations

Building Regulations are sets of prescriptive national building standards which were first introduced in 1965. These regulations have been followed by the Building Act 1984, which consolidates certain enactments concerning buildings and related matters (Code, 2000). Since then, and with increasing focus on low-carbon initiatives and sustainability, the Building Regulations are also amended on a regular basis - currently the 2013 version. There are different regional standards; Wales will have own Building Regulations in 2015, which set higher insulation and energy standards. (Tricker and Alford, 2013). These regulations basically contain the rules for construction work that every new and altered building needs to comply with to improve overall quality, safety and accessibility, and to limit environmental impact. To facilitate checking compliance, the Building Regulations are supported by a statutory guidance approved document providing general guidance, and practical examples and solutions to demonstrate how to achieve compliance (Government, 2012).

2.1.2 Standard for Building Research Establishment Environmental Assessment Method (BREEAM)

BREEAM was originally developed in the UK in 1990 as the most comprehensive environmental assessment method (Global, 2011b). It has established the foundation for effective approaches around the world to measure and describe the environmental performance of buildings. The main aim of introducing BREEAM was to mitigate the impact of buildings on the environment and to increase recognition of buildings according to their environmental benefits (Kasim et al., 2013). In order to address these issues, BREEAM sets standards and best practices to measure the sustainability of buildings using the benchmarking approach (Skopek, 1999). The development of these standards occurs through the national consultative process (Alyami and Rezgui, 2012). BREEAM standards incorporate environmental measures across a wide range of issues, including global influences, local impact and indoor performance (Doggart and Baldwin, 1997). The basis of BREEAM assessment is to compare key issues of the design with defined criteria for best practice in sustainable design. These assessment criteria are expressed in different terms according to their nature; for example, some aspects are expressed as quantitative metric values. To meet these criteria, assessors may need to conduct numerical procedures, calculations or enumerations (Pohekar and Ramachandran, 2004). When the assessment criterion is expressed in contextual subjective measures, professional interpretation is required to re-organize the information context within the statement, and to make the assessment accordingly (Haroglu, 2012). Although there are numerous explicit assessment criteria in the BREEAM standard, there are also a considerable number of ambiguous definitions that are implicitly embedded within the nested statements. These criteria are only understandable by professionals or people who have knowledge in the relevant domain. The involvement of

BREEAM assessor is fundamental in judging the compliance requirements (Kasim et al., 2012a) . In addition, there are an overwhelming number of assessment criteria which requires compliance with a strategy or sub-regulation within the regulations (Global, 2011b). Although BREEAM critically covers a diverse range of issues regarding building performance and sustainability, its complicated format reduces its transparency and makes the assessment process complicated, time-consuming and expensive. These aspects depend to some extent on whether a standard assessment form can be used, or whether one needs to be created due to the type or complexity of the building.

2.1.3 Code for Sustainable Homes (CfSH)

The Code for Sustainable Homes (C'f'SH) (Government, 2010) is the national standard for assessing, rating and certifying the sustainability performance of homes in England, Wales and Northern Ireland. It was first introduced in 2007 (Council, 2011).The aims of (CfSH) is to encourage continuous improvement in sustainable home design and to promote higher standards over the current statutory requirements (McManus et al., 2010). The code provides nine measures for sustainable design; namely: energy, water, materials, surface water runoff, waste, pollution, health and well-being, management and ecology. Each of these sections awards credits according to the building's performance. In these sections, an overall rating is given of between 1 to 6 stars. Although C'f'SH is currently the most important policy for assessing homes' sustainability, it has been criticised by some researchers. (McManus et al., 2010) that C'f'SH is unable to deliver its goal for designing sustainable homes and it may obstruct house building in UK. Furthermore, it has received some criticism regarding the deficiency and expense of compliance checking according to government requirements.

2.1.4 Summary

The number of building codes, regulations and best practices is increasing rapidly, especially in the field of sustainable engineering, and the complexity of these regulations is growing massively to meet the requirements for sophisticated efficient design with low carbon footprints. The majority of these standards and regulations are composed with highly technical guidance. There are a diverse range of aspects covered by building codes and regulations falls under different categories, for example; energy and environment regulations, and low consumption and energy efficiency regulations. Despite the significant differences in terms of their originality, historical development and emphasis on environmental issues, the standards have similarities in major purposes and compliance procedures.

The development of these regulations is directed from feature based exigency toward performance based requirements; for example, the energy-efficient design assessment is derived from the features of the design such as material specification and the energy utilities, which is performance-based. The traditional methods of presenting these compliance requirements are criticised for their limitations by (Gupta and Dantsiou, 2013); these criticisms signal a major shift in thinking towards a new covenant in setting up the regulations to meet the modern era. Changes in building design and operations have been occurring continuously; for example the processes are becoming more ICT (*information communications technology) oriented.* In the face of such trends, legislation, standards and regulations need to meet these conceptual challenges (Rezgui and Medjdoub, 2007). The traditional textual presentation of compliance requirements need to undergo a transformation into more logical expressions in a digital format that complies with the automated extraction of data while preserving the same context to deliver their requirements. Although there are enormous barriers to achieving such conversions, there would be a great benefit of developing a regulatory-based IT infrastructure for the long-term (Alavi and Leidner, 1999). Such developments could enhance the application of verifiable smart compliance measurement procedures, to efficiently assess the environmental sustainability of buildings.

2.2 Assessment Methods and Rating Systems

2.2.1 BREEAM assessment method

The BREEAM (Building Research Establishment Environmental Assessment Method), established in the UK in 1990, is the first such comprehensive building performance assessment method (LiuShaoyu, 2002). The basis of the scheme is to grade the individual building according to its environmental performance in the form of credits. The BREEAM mechanism for conducting the environmental assessment of buildings has initiated the development of environmental assessment methods both nationally and across many regions of the world. Different versions have been developed in the UK to include the requirements of buildings under refurbishment, new and existing buildings for different operational purposes; residential buildings, office buildings, retail, *etc*. Internationally, versions have been - or are being - developed for Australia, Canada, New Zealand and Hong Kong (Haapio and Viitaniemi, 2008).

BREEAM assessment depends on three scales of environmental impact; global, local and indoor-related issues. The BREEAM assessment method has many similarities with the other environmental sustainability assessment measures. The process methodology of BREEAM assessment - described in Figure 2-1 - is to quantify impacts in different categories as numerical expressions of category score. The score is then factorised by a weighting factor of environmental impact to produce a single score of credit; these credits, when added together, represent the performance of a building. The final rating is presented as *'Pass', 'Good', 'Very Good', 'Excellent' and 'Outstanding*', according to the achieved number of credits, as illustrated in table 2-1.

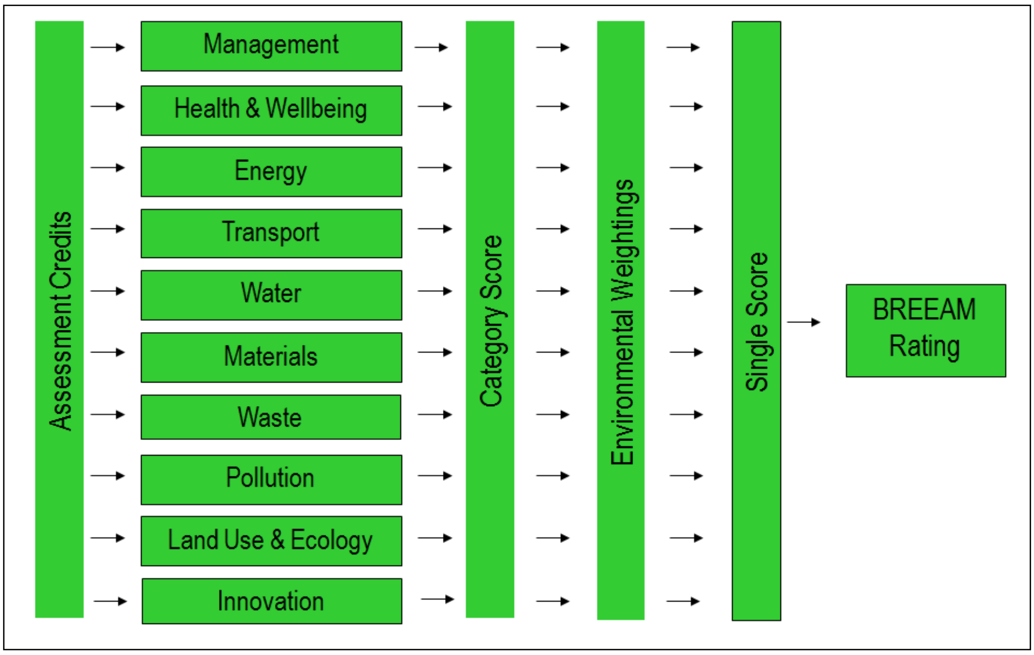

Figure 2-1 BREEAM assessment process

There are nine different dimensions assessed in BREEAM, namely: management, materials, health and well-being, energy, transport, water, land use and pollution. Each issue is then divided into sub-categories, which are required to meet certain criteria to achieve BREEAM rating benchmarks and to meet minimum BREEAM standards. According to their environmental impact, the weighting of these categories is different, as illustrated in Table 2-2.

Table 2-1 BREEAM rating

BREEAM Rating	% Points
Outstanding	≥ 85%
Excellent	≥70%
Very Good	≥55%
Good	≥45%
Pass	≥30%
Unclassified	<30%

BREEAM assessment for a particular issue depends on the context of the requirement; for example, quantifiable issues such as energy, water, CO2 emissions, and materials, can be obtained numerically by setting some calculations and comparing with a benchmark to examine compliance with a certain requirement. While some issues are subjective and depend on the performance of the building under different conditions such as transport, health and wellbeing, Figure 2-2 illustrates the formulation of the information model concept for the BREEAM framework. As indicated in Figure 2-2, in BREEAM, each of the nine initial dimensions is divided into multiple sub-categories, resulting in a highly-elaborate framework. As a result, BREEAM assessment and certification is a highly-complex, rigorous and costly process; the huge amounts of data at every stage of the project make it difficult to conduct BREEAM assessment continuously and accurately. In particular, when the assessment is considered at a later stage, it reduces the influence that BREEAM can have on a project, and may result in a desired rating being unobtainable, or being obtainable only through additional investment (Reed et al., 2009). The final assessment depends on the overall building performance, therefore it cannot be conducted - and certification is not received - until construction is complete. The certification is issued after the decision of an assessor, based on collation of rigorous and credible evidence of building compliance (Global, 2008).So the final decision is associated with the availability of correlating information that convinces the assessor.

Table 2-2 Environmental weighting factors of BREEAM issues

Environmental category	abbreviation	Weighting factor
Land Use and Ecology	LE	10%
Water	Wat	6%
Energy	Ene	19%
Materials	Mat	12.5%
Health &Wellbeing	Hea	15%
Transport	Tra	8%
Waste	Wst	7.5%
Pollution	Pol	10%
Management	Man	12%
Innovation(Additional)	Inn	10%
Total		110%

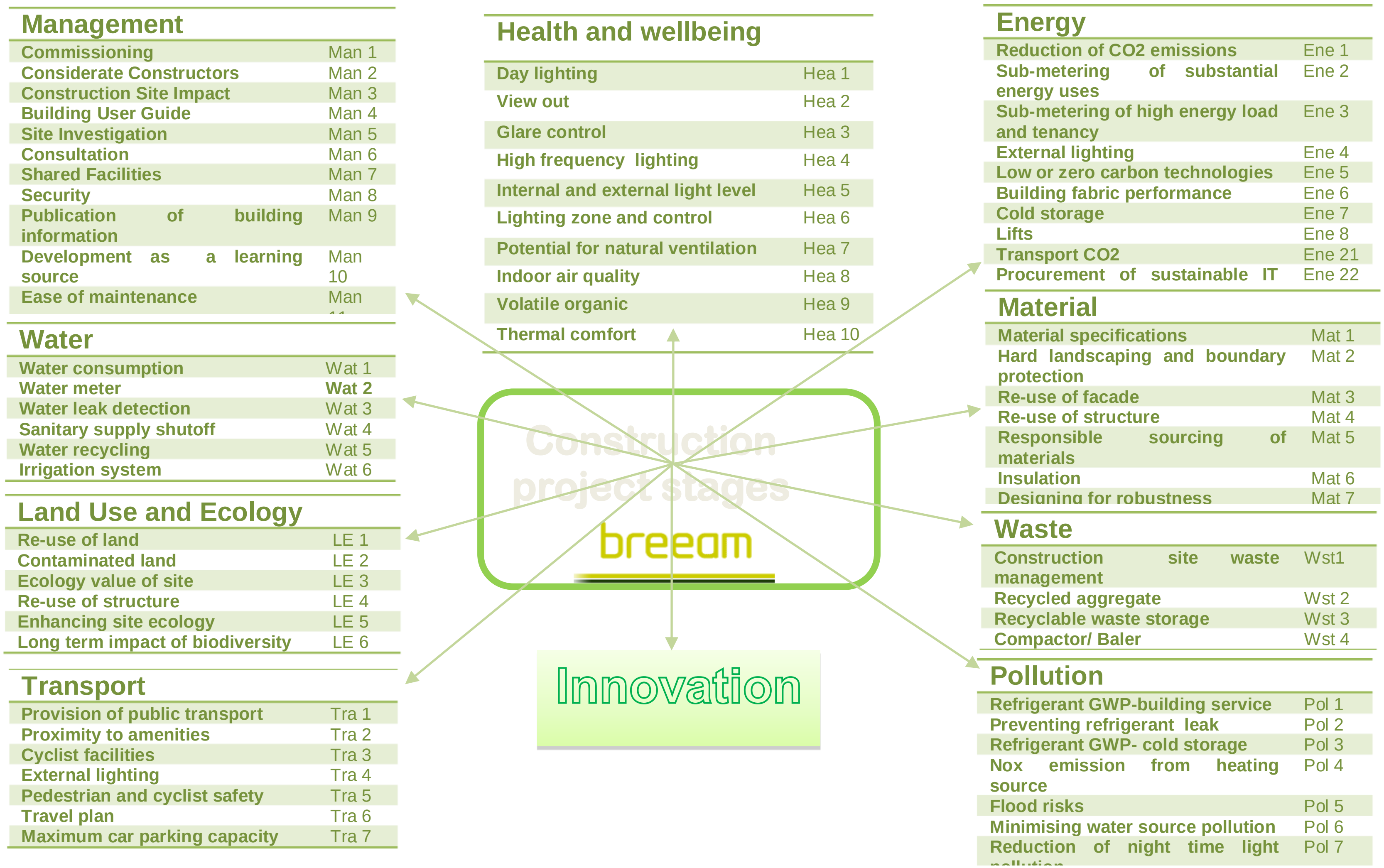

Figure 2-2 Formulation information model concept for BREEAM framework

2.2.2 LEED rating system

The Leadership in Energy and Environmental Design (LEED) rating system is currently one of the most widely used rating systems globally. It was developed by the United States Green Building Council (USGB) in 1998; it was first published in 2000 to provide stakeholders in building design and operation a concise framework for assessing the sustainability performance of buildings. Based on the same mechanism, eight more rating systems have been developed to provide practical and measurable green building design solutions for different types of buildings (Council, 2006b). Internationally, there are a considerable number of LEED-accredited professionals, as recorded by The Green Building Certification Institute website. In terms of the number of applications, the UK is listed as the fifth highest country with 66 LEED applications, behind the US, Canada, UAE and China (Cidell, 2009). Compared with BREEAM, which has been able to adapt to local contexts in different regions across the world, LEED has not been developed in this way (Reed et al., 2010). Although there many differences between the two schemes, LEED also possesses a larger number of similarities to BREEAM in terms of the assessment process. LEED credits are awarded based on six categories of sustainable design features; sustainable site, water efficiency, energy and atmosphere, ‘materials and resources, indoor environmental quality and innovation in design. The weighting of these categories is based on their environmental impact, as shown in Table 2-3.

Table 2-3 Environmental weighting factors of LEED issues

Environmental category	Maximum points	Weighting factor
Sustainable Site	26	10%
Water Efficiency	10	9.1%
Energy& Atmosphere	35	31.9%
Materials &Resources	14	12.7%
Indoor Environmental Quality	15	13.6%
Innovation in Design	6	5.5%
Regional Priority	4	3.6%
Total		100%

The number of points awarded are added together to indicate an overall performance category of ‘Platinum’, ‘gold’, ‘silver’, ‘classified’ or ‘unclassified’, as illustrated in Table 2-4. The LEED assessment process has been criticised for its lack of consideration of many aspects of sustainable design, and the difficulties for handling diverse sets of fragmented information (Papadopoulos and Giama, 2009). However, the assessment is normally conducted by the design team and there is no need for a trained assessor, although extra credits can be attained if a member of the design team is a LEED-accredited professional.

Table 2-4 LEED rating scale

LEED Classification	Points
Platinum	≥ 80
Gold	60-79
Silver	50-59
Classified	40-49
Unclassified	<40

2.2.3 CASBEE

CASBEE (Comprehensive Assessment System for Building Environmental Efficiency) was developed by the International Initiative for a Sustainable Built Environment in Japan in 2001 (Murakami et al., 2002). CASBEE is described as a family of assessments, because it utilises four major tools to assess different stages of a building's lifecycle; the pre-design assessment, new construction, existing buildings and renovation. The concept of assessment is quite different from that demonstrated in BREEAM and LEED assessment fundamentals. The CASBEE mechanism distinguishes environmental load (L) from quality of building performance (Q), and the results are presented as a measure of building environmental efficiency (BEE) or eco-efficiency. Each of the two factors (Q&L) represents categories for sustainable building design features; Building Environmental Quality and Performance (Q) is categorised into 'Indoor environment', 'Quality of services' and 'Outdoor environment on site', While Building Environmental Loadings (L) is categorised into 'Energy', 'Resources and materials', 'Reuse and reusability' and 'Off-site environment'. The criteria of each category is assessed in the form of levels ranging from Level 1, representing a minimum achievement, to Level 5, representing the highest achievement.(Consortium, 2004). A CASBEE classification depends on the value of Building Environmental Efficiency (BEE), which is the ratio of environmental performance (Q) to environmental load (L). Depending of the BEE value, a building can be classified on a five point scale from poor to excellent (Table 2.5). The assessment process is rigorous and complex, and requires the gathering of fragmented information across the domain of sustainable construction (Aotake et al., 2005). However, the CASBEE assessment process does not require a trained assessor; it is a self-assessment system, which allows the user to be able to improve the performance of his/her designs several times until they achieve the optimum value. (Fowler and Rauch, 2006a).

Table 2-5 CASBEE rating scale

BEE (Q/L)	CASBEE Class
3 $>$ BEE & Q$\geq$ 50	S= excellent
1.3 $\leq$ BEE $<$ 3	A
1 $\leq$ BEE $<$ 1.49	B^{+}
0.5 $\leq$ BEE $<$ 1	B^{-}
0 $\leq$ BEE $<$ 0.5	C = Poor

2.2.4 GBtools or SBTools

GBTools was developed by the International Framework Committee, for the Green Building Challenge in 1998, by professionals from more than 25 countries across the world (Cole and Larsson, 2002). GBTool is distinguished from other sustainability assessment methods by its adaptability and its capability to prioritise several regional aspects. The assessment process involves consideration of buildings' cultural values, traditions and the available regional technologies. GBTools assesses the environmental sustainability categorised under several issues, namely; 'Project planning and development', 'Energy and resource consumption', 'Environmental loading', 'Indoor environmental quality', 'Service quality', 'Social and economic aspects, and 'Cultural and perceptual aspects'. The weighting factor of each issue is different, as illustrated in Figure 2-6. The scale of assessment is a numerical expression, and ranges from -1 to +5, based on a local benchmark of "typical" practice. According to this scale, buildings with a negative value score represent a performance of 'below typical practice', while the positive linear range of +1 to +5 represents good to very high performance.

Table 2-6 SBTool environmental weighting edited from (Alyami and Rezgui 2012)

SBTool categories	weighting
Site selection, project planning and development	7.6
Energy and resource consumption	21
Environmental loading	25.2
Indoor environmental quality	21
Service quality	15.1
Social and economic aspects	5
Cultural and perceptual aspects	5

2.2.5 Review of classifications systems and a comparison of assessment methods

Environmental assessment methods and rating systems were created to satisfy the need for the construction industry to achieve sustainable buildings. The assessment mechanisms differ, ranging from rating systems, assessment frameworks, technical guidelines, checklists and certificates (Haapio and Viitaniemi, 2008, Annex, 2007, Khasreen et al., 2009) cited in (Ding, 2008b). In order to facilitate the analysis of available tools, and to understand the differences between them, classification systems have been created. There are two well-known classification systems available: Assessment Tool Typology, which is developed by the ATHENA institute, and the IEA Annex 31 project. In the ATHENA classification system, the tools are classified into three levels, focussing on the purpose of the assessment and the assessment process (Trusty, 2000). According to the IEA Annex 31 project, this classification is wider than that of ATHENA; it is based on the "energy-related environmental impact of buildings" (Todd et al., 2001).

The number of sustainable building rating systems has been increasing during the last decade, and currently there are more than 34 environmental assessment tools available on the market (Fowler and Rauch, 2006b). Some of these tools are presented in Table 2-7; this highlights a brief definition of a tool, its origin and citation information. These tools are developed for different purposes, such as research or decision making, which gives rise to tools used by different types of users, such as researchers, designers, architects, consultants, owners, and authorities.

Table 2-7 Environmental Assessment Tools Across the World

Tool	Definition	Origin	references
ABGR	Australian Building Greenhouse Rating	Department of Commence, NSW, 2005	(Bannister, 2005)
AccuRate		CSIRO, 2006	(Ding, 2008a)
BASIX	Building sustainability Index	Department of Infrastructure, Planning and Natural Resources, 2004	(Ding, 2008a)
BEPAC	Building environmental performance assessment criteria	Canada, 1993	(Cole, 1998, Crawley and Aho, 1999)
CEPAS	Comprehensive environmental performance assessment scheme	HK, 2001	(Cole, 2005)
CPA	Comprehensive project evaluation	UK, 2001	(Ding, 2008a)
DQI	Design quality indicator	UK	(Gann et al., 2003)
EMGB	Evaluation manual for green buildings	Taiwan, 1998	(Lin, 2004)
EPGB	Environmental performance guide for building	Department of Public Works and Services, NSW	(Ding, 2008a)
GHEM	Green home evaluation manual	China, 2001	(Ding, 2008a)
GreenStar		Green Building Council	(Roderick et al., 2009)
HKBEAM	Hong Kong building environmental assessment method	Hong Kong, 1996	(Yik et al., 1998)
NABERS	National Australian building environmental rating system	Department of Environment and Heritage, 2001	(Chen et al., 2006)
NatHERS		CSIRO	(Ding, 2008a)
SBAT	Sustainable building assessment tool	South Africa	(Cole, 2005)
SPeAR	Sustainable project appraisal routine		(Ding, 2008a, Cole, 2005)

Between all of the available sustainability assessment tools and methods, there are four major players emerging, which were explained earlier in this chapter; *'BREEAM', 'LEED, 'CASBEE', and* ***'****SB tools'* (formally known as GBTools). It was reported by (Chew and Das, 2008, Alyami and Rezgui, 2012) that these schemes are the most reliable in the global context. Table 2-8 presents a general comparison between these tools, highlighting their weaknesses and strengths. Although these tools provide an objective response to current environmental problems, none of them are able to assess all aspects of a building equally.

There remain some limitations related to the amount of data that needs to be collected to make an assessment, in addition to the time, effort and cost of the assessment. Furthermore, these methods rely on a large amount of data, making assessments time-consuming, costly and labour intensive. In spite of the range of differences between the processes of implementing environmental rating systems, they all aim to promote design, construction, and operating systems in achieving high-performance and, through integration with analysis tools, to achieve integrated solutions to the management of project data at every stage of a construction project (Rezgui, 2007). The objective solution to the current assessment methods is to promote the holistic assessment process through the incorporation of information technologies at early stages of the design. This could facilitate management of the process of building performance assessment, when the building information and the data from simulation tools optimized and controlled digitally and dynamically according to the targeted performance criteria.

Table 2-8 comparison between environmental assessment method

Assessment Method	BREEAM	LEED	CABSEE	GBTools
Assessment Categories	Land Use and Ecology Water Energy Materials Health &Wellbeing Transport Waste Pollution Management Innovation	Sustainable Site Water Efficiency Energy& Atmosphere Materials &Resources Indoor Environmental Quality Innovation in Design Regional Priority	**Building Environmental Quality** environment Quality of services Outdoor environment on site Building Environmental Load **Energy** Resources and materials Reuse and reusability Off-site environment	Site selection, project planning and development Energy and resource consumption Environmental loading Indoor environmental quality Service quality Social and economic aspects Cultural and perceptual aspects
Rating scale (High to low)	Outstanding Excellent Very Good Good Pass Unclassified	Platinum Gold Silver Classified Unclassified	+5 +4 +3 +2 +1 -1	S A B+ B - C
Assessment	• Trained BREEAM Assessor/BRE	• Design team/ USGBC	• self-assessment system	
Strength	• Comprehensive • Different criteria may achieve the desired rating • Allow comparison and benchmarking	• Lots of information available • No need for trained assessor • Strong marketing • Integrated with BS tools	• Compares environmental load with quality of building performance • a self-assessment system • No need for assessor • Allow for continuous modification • Quality of services	• Flexibility and adaptability • No need for trained assessor • Assess cultural values and regional traditions • Quality of services • Covers economic issues
Weakness	• Very exact requirement • Expensive • Complex weighting system • Requires gathering fragmented information • Limited adaptability	• Based on US system • Limited adaptability • Do not consider building services • Lack in assessing many aspects of sustainable design	• Require gathering fragmented information about the building • Lack in assessing many aspects of sustainable design	• Has 150 criteria for sustainable design which increases complexity • Deals with fragmented information covering different aspects

2.3 Sustainability analysis tools

Sustainability compliance checking of buildings is always associated with the use of building performance and energy simulation tools. These tools predict the performance of a building according to its design features (Maile et al., 2007). The number of energy simulation tools is increasing with the increased demand for energy-efficient buildings. In the past, the integration of energy simulation tools with 3-D modelling was limited to the geometry using file-based format such as DFX. The links between tools were developed based on Application Program Interfaces (APIs); with the emergence of BIM solutions, data exchange has developed to include product and object information using data exchange models such as IFC and gbxml (Stumpf et al., 2009). This section describes some energy simulation tools, highlighting their capabilities to support compliance checking.

2.3.1 Green building studio

GREEN Building Studio (GBS) is a set of web-based energy analysis software tools owned by Autodesk (Azhar et al., 2009). GBS exports the gbXML file from BIM tools to conduct energy simulation. The simulation results are used to measure the building performance according to a benchmark of energy efficiency and occupants comfort, and includes: *'Annual energy cost' ' Lifecycle energy costs (30 year)' 'Annual energy consumption (electric and gas)' 'Peak electric energy demand', 'Lifecycle energy consumption (electric and gas)', 'Onsite energy generation from photovoltaic and wind systems', ' Water use analysis', 'Assistance with day lighting using glaze factor calculations, 'Natural ventilation potential calculations, 'Carbon emission calculations, (Autodesk, 2013).* In addition to building orientation, the effects of sunlight path and shadowing can be visualized on the model. The benefits of these features are prominent, since they allow for optimization of the building design, and comparison of alternatives.

Although GBS provides valuable results concerning sustainable building design, it also has some limitations (TOOLS, 2009). The calculations behind the tool's interface require a significant amount of information regarding the design features. This information is both time-consuming to collect, and likely to be unfamiliar to most building designers. In addition, GBS does not facilitate adequate modification, although it gives some design alternatives

2.3.2 Ecotect

Ecotect is a building performance simulation tool owned by Autodesk. It has been defined as *"a complete building design and environmental analysis tool that covers the full range of simulation and analysis functions required to truly understand how a building design will operate and perform"* (Autodesk, 2008). The tool has the capability to conduct the following analyses; 'energy analysis', 'thermal analysis', and 'lighting/shading'. Although the tools offer interesting features such as a quick and precise results display and capabilities for model viewing, there are still some limitations related to data exchange and inconsistency (Azhar et al., 2009)

2.3.3 IES

Integrated environmental solutions (IES) are known as the global leader in measuring sustainability (IES, 2008); their virtual environment has been widely used for sustainability analysis, and it has integration capabilities with BIM tools such as Autodesk Revit (Azhar et al., 2011). IES exports files in gbxml format from BIM modelling tools, and conducts sustainability analyses directly, such as solar analysis, visualization of sun's path and solar gains inside the building, and quantifies the impact of solar control features such as overhangs and vertical fins. IES also has the ability to perform simulations to create a foot-candle map on the floor plan, and create photo-realistic 3D renderings. Regarding natural ventilation analysis, IES can assess the performance of natural ventilation using operable windows. With IES, it is possible to edit building geometry and to modify the design, such as placing additional windows into the model, and creating shading overhangs. However, the gbxml format is only uni-directional, and the model cannot be released in its original format. IES also has the ability to check the model compliance with part L of the Building Regulations, and to conduct assessment against a LEED rating system.

2.3.4 Energy Plus

Energy Plus is also widely used to perform building simulations. There are a number of software tools that are linked to Energy Plus, in order to provide an interface to streamline energy efficiency calculations for BREEAM and LEED rating systems. For example, LEED certification uses the AECOsim Energy Simulator; this system is rationalised by Energy Plus for building performance simulation, while, MagiCAd, EcoDesigner Star, DesignBuilder, and Riuska have been BREEAM-proved for the calculation of energy-efficiency issues (Oy, 2013, DOE, 2013).

2.3.5 Summary

Building energy modelling tools provide an efficient, simple method for predicting the regulated energy use of new and existing buildings. They have the potential to play an important role in the future energy use profile of the building. Environmental assessment methods rely on a number of these energy efficiency calculation tools. For example, approved dynamic simulation models and the Simplified Building Energy Model (SBEM) are used for BREEAM accreditation. However, these tools are not considered as design tools (Raslan and Davies, 2010), and cannot be used for system sizing.

The number of software tools used for sustainability analysis, energy analysis and CO2 emission calculations are vast. IES<VE> has the ability to conduct energy analysis and examine building compliance with part L of the building regulations. In addition, the functionality of IES has been expanded to include checking against the LEED rating system, and calculating the score for energy-related issues. Another system that belongs to the same IES family is TaP, which claims to manage and automate the certification process for both the BREEAM and CSH rating systems. Building information models intend to provide the information for building simulation tools as an attempt to automate sustainability compliance checking (Crawley et al., 2001). Different formats for data exchange are currently available between BIM tools and energy analysis tools. For sustainability analysis on BIM models, gbXML and Industry Foundation Classes (IFC) are currently used for data transfer. However, there are some limitations in their usage; gbXML is not comprehensive and it lacks lifecycle consideration, and in addition, any modification to a gbXML file cannot be exported back to BIM tools, since again it is a one-way data exchange.

The use of IFC also has limitations; it does not include all of the information needed for sustainability compliance checking. IFC needs to be extended to contain more energy and performance concepts, in order to be compliant with the domain of sustainable design requirements. Table 2-9 demonstrates a comparison between some well-known energy analysis software, highlighting the analysis result, and data format and exchange functions.

Table 2-9 A comparison between energy simulation tools

Energy analysis tools	Exchange data format	requirements	Analysis results	Modification possibility	Check against building regulation	sustainability assessment	Possibility for integrated sustainability assessment
GBS	gbxml	Simplified building model	Annual energy cost • Lifecycle energy costs • Annual energy consumption • Peak electric energy demand (kW) • Lifecycle energy consumption • Onsite energy generation from photovoltaic and wind systems • Water use analysis • Assistance with day lighting using glaze factor calculations • Natural ventilation potential calculations • Carbon emission calculations	Give design alternative	NO	LEED	Achievable
Ecotect	gbxml	Building mass model	Sunlight path and Shadowing effect Optimized orientation Solar intensity	Give design alternative	no	no	no
IES	gbxml	Whole building model	Annual energy cost • Lifecycle energy costs • Annual energy consumption • Peak electric energy demand (kW) • Lifecycle energy consumption • Onsite energy generation from photovoltaic and wind systems • Water use analysis • Natural ventilation potential calculations • Carbon emission calculations	Allow modification	Part L	LEED	achievable
Energy plus	IFC	Import gbxml into ecotect and export IDF into energy plus	Primary energy Pollutants emissions. Financial indicators	no	no	LEED	achievable

2.4 Conclusion

Sustainability regulations, environmental assessment technologies, and building performance simulation tools, are the fundamentals of efficient, sustainable design and construction, with a low carbon footprint. The full benefit of these methods has not yet been realised.

It can be concluded in this chapter that the ultimate benefit of sustainability compliance checking can be achieved through three major phases. The first phase is to convert standards and regulations into more precise, explicit logical expressions. The second phase is to integrate building performance simulation tools with compliance checking tools. The third phase is to embed the regulatory requirements and the data from building simulation tools automatically into the compliance checking environment. This will result in a more efficient solution with less investment required, and will minimise the effort required in checking building sustainability compliance automatically - this is illustrated in Figure 2-3.

There are a considerable number of challenges that limit the achievement of such integrated solutions. For example; the regulations and standards have not been designed in a manner that allows them to be directly automated; instead they are contained in textual documents that require human interpretation and processing.

Also, building performance simulation tools lack interoperability with the requirements of sustainable design specified by sustainability regulations and standards and best practice.

It seems that the major issue is associated with information format, storage and exchange. With the evolution of BIM technologies and data sharing scope, the potential for advanced solutions to streamline sustainability compliance checking has been intensified. This issue will be explained in detail in Chapter three of this thesis.

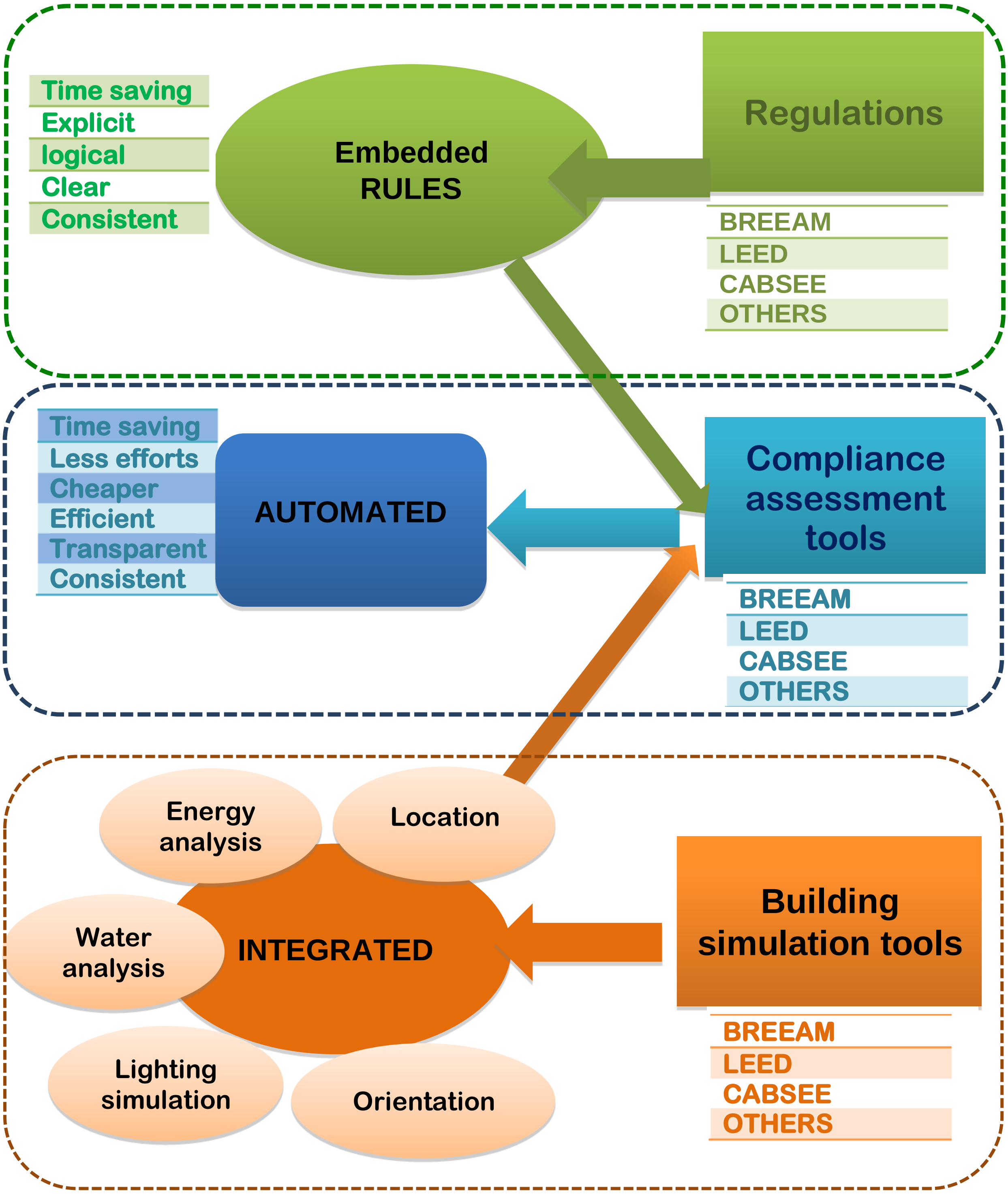

Figure 2-3 Framework for integrated compliance checking solutions

Chapter 3

Information Management and BIM Interoperability

3.0 Introduction: Information management in the construction industry

The construction industry is an information intense sector. During the life cycle of a construction project, a series of activities and processes take place by multiple project partners simultaneously. Every task is dependent on the availability of comprehensive sets of data and information. These data need to be collected, stored and processed at every stage of a construction project. Typically, that requires substantial effort, time and significant investments. The role of construction project management and coordination is to critically prioritise these processes and to deliver a sequence of integrated activities with minimal individual effort and time and maximum cost reduction (Laudon and Laudon, 2011). Nevertheless, the complexity of information handling is increasing with the evolution of the new technologies of collaborative project delivery. Due to the complexity and diversity of information during the lifecycle of a construction project, the efficiency of information management within the construction industry has become crucial. Furthermore, it is an integral part of successful project management (Betts et al., 1991, Rezgui, 2001, Akintoye et al., 2000).

One of the most important issues in achieving interoperability in construction projects is information and knowledge sharing. The main elements shared by the project team throughout the construction process work flow are represented by drawings and documentations. These artefacts are exposed to continuous manipulation and amendments. Manual paperwork, drawings and documentation existed for centuries until the introduction of CAD in the early 1980s (Medjdoub et al., 2001). CAD technology had a very influential impact on the construction industry, being the first to allow for sharing design data and drawings, either via proprietary drawing formats or later via de facto standards such as DXF (Drawing/Data Exchange Format) with the added measurements, dimensions and layering (Boddy et al., 2007).

The use of CAD was very effective in providing the opportunity for data manipulation, sharing and integration. However, it was mainly limited to the geometrical information of the project (Brown et al., 1996). The use of CAD continued in its development to introduce the object oriented CAD in the early 1990s. The initial data objects represented in these systems were roofs, floors, walls, doors, windows and related plants and equipment. Object oriented CAD introduced storage for non-graphical data about a building further to the geometrical representation (Eastman et al., 2005).

The main objective of the promotion with data presentation is to facilitate transparency of information sharing between parties in line with governments obligations and legal legislations (Otjacques et al., 2007). This topic has opened the doors for a wide domain of research projects towards new information sharing approaches. To that end, researchers and commercial application developers within the construction industry have started to develop tools to migrate from document centred approaches towards modelling and computer integrated approaches and furthermore, to manage and manipulate complex data models (Fischer et al., 2004, Männistö et al., 1998). The development of knowledge management systems over time has overturned significant challenges. (Boddy et al., 2007) have concluded three generations of knowledge sharing which are summarised in figure 3-1. The first generation is described as document- based management systems where documents are perceived as ‘‘black boxes” and the knowledge content requires human interpretation. The researchers argued that the first generation can be characterised as technology driven, and is mainly focused on business process automation through IT. The adoption of office automation tools has facilitated the production of electronic documents and the computer has aided the introduction of drafting and design(Rezgui and Miles, 2009).

Later, researchers and commercial application developers recognised the necessity to develop tools to manipulate complex building models. Hence, they developed the second generation of knowledge management which is described as ‘knowledge conceptualisation and nurturing’. IFCs and the recent BIM are examples of these Knowledge Management systems which are characterised by their codification, and conceptualisation. This second generation of KM has also seen the emergence of ontology (Rezgui, 2007).
The third generation of KM can be described as knowledge value creation. It has been initiated with the emergence of the primary aspects of sustainability to deliver human and environmentally friendly construction. The researcher also defines the value creation process as “any process of creating knowledge value, as subjectively perceived by users, out of existing knowledge practices across an organization” (Rezgui, 2007).

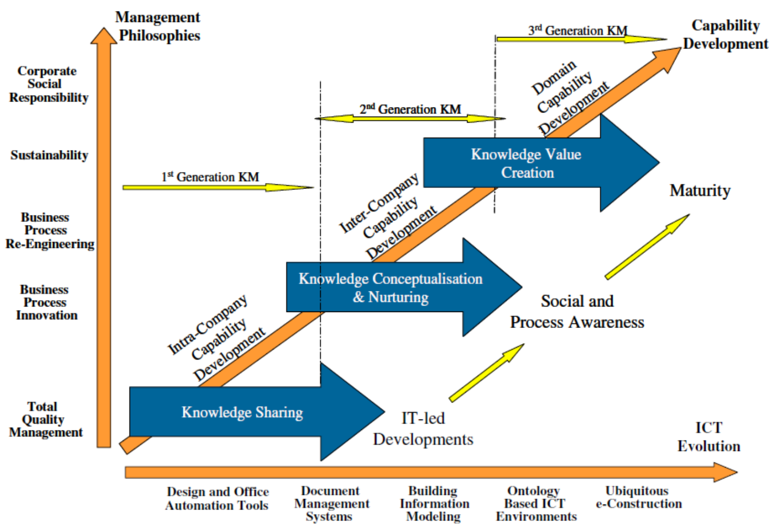

Figure 3-1 Generations of KM in AEC (Rezgui 2007)

3.1 Building Information Modelling

The phrase “BIM” was originally used in the late 1970s by Professor Charles M. Eastman of the Georgia Institute of Technology (Eastman et al., 2008a). However, it perhaps did not become widely recognised in its current context until Autodesk brought out the architectural software package known as “Revit” in the 1990s, which enhanced the concept of BIM through information modelling during the design. Charles Eastman described BIM in his publication Building Product Models: computer environments supporting design and construction (CRC Press, 1999) as follows: “BIM is a digital visible model of the building process to facilitate exchange and inter-operability of information in digital format.” (Eastman et al., 2008b). Others have identified BIM as a ‘modelling technology and associated set of processes to produce, communicate, and analyse building models.’ (Eastman et al., 2005).

BIM is revealing new modes of sharing and adopting information in the architecture, engineering and construction (AEC) industries. It has been proposed for integration with computer- aided design in the last decade, yet it has no single, widely-accepted definition. A building information model incorporates both syntactic and semantic information about a project. More specifically, building information models “allow for multi-disciplinary information to be superimposed within one model and provide the opportunity to capture, manage and present data in an appropriate way” (Azhar et al., 2012). The 3D representation of the model achieved by computer- aided design (CAD) and other developed schemes, is combined with BIM data, and stored in a logically-centralised database, to be managed by software throughout the building’s life cycle (Kam et al., 2003, Welty and Guarino, 2001). Essentially, a building information model constitutes an information representation system that includes definitions and property descriptions of building components, in addition to their graphical depiction. A BIM representation also includes the relationship between entities beyond the object-level. This advent in information representation began to play a significant role in automated information processing in the construction industry. This automation is becoming possible when the information configuration is enriched enough to accomplish specific information-handling operations (Lima et al., 2005a). This leads to the evolution of a new wave of BIM data exchange between multiple analysis tools, to achieve integrated solutions within a single model (Rezgui, 2007).

In architectural engineering, the BIM model appears to cover geometry, spatial relationships, orientation and geographic information (Howell and Batcheler, 2005), while in structural engineering, BIM covers the quantities and properties of components and objects, and the materials of the building structure (Enevoldsen and Sørensen, 1994). BIM covers the entire building life-cycle behaviour, including the construction processes and facility operation. The quantities and properties of objects and materials (for example the manufacturer's details) can be obtained easily; furthermore, dynamic information about the building, such as sensor measurements and control signals from the building systems, can also be incorporated within BIM to support an analysis of the building operation and maintenance (Azhar et al., 2008).

The term 'BIM Level 3', is widely accepted as an integrated framework to manage a building's performance during its lifecycle, when the aim is integration with sustainability tools to achieve a high performance building. BIM Level 3 provides a database of coordinated information allowing for continuous and immediate analysis to be conducted at any stage of the design. Throughout this thesis, the term BIM will correspond to this definition.

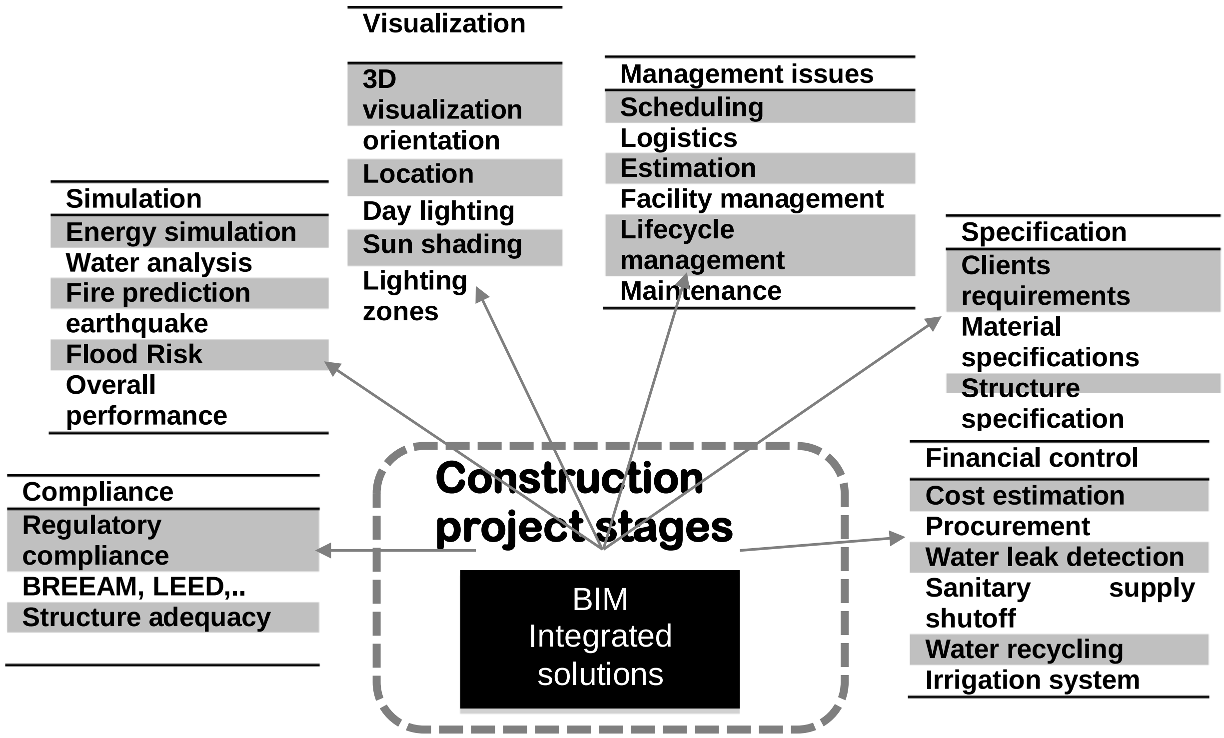

Figure 3-2 BIM integrated solutions

Figure 3-2 shows that the majority of information required to examine a building's sustainability could be obtained from the BIM model. In this case, if a BIM model is used in the early stages of a design, the design teams can put more effort into performing parametric studies and analysing the sustainability-related aspects of the design. The majority of sustainability aspects can be analysed continuously during the modeling phase, and the real-time performance can also be dynamically monitored as the design proceeds. However, there are considerable challenges which limit the application of such integrated solutions. For example, building performance simulation tools lack the inter-operability with the requirements of sustainable design, as specified by sustainability regulations, standards and best practice.

The BIM framework is multi-dimensional, i.e., the activities within the BIM field are varied; however, technologies, processes and policies are the main interacting activities (Succar, 2009). The interaction between these activities is a push-pull knowledge mechanism; a push mechanism transfers knowledge and data between domains, while a pull mechanism transfers knowledge in order to satisfy some request by another domain. The interaction within the BIM environment requires a coordinated data flow between domains. This includes various types of data such as the transfer of databases, spreadsheets and images between computer systems (Kyle et al., 2010). Data-flow throughout the design, implementation and maintenance of a construction project can be described as data interchange and data exchange. Data exchange occurs when transferring non computable / structured data, such as the exchange of 2D drawings out of a 3D object-based model. This exchange potentially results in the loss of some geometric and semantic data. A data interchange, as stated by Bilal Succar (Succar, 2009), is an interoperable data exchange between parties. Inter-operability is defined as "the ability of two or more systems or components to exchange information and to use the information that has been exchanged (Geraci et al., 1991) .

The levels of inter-operability in BIM are developing. The most effective way to understand these levels is to refer to the BIM Maturity Diagram, prepared by Mervyn Richards and Mark Bew in (Oti and Tizani), as illustrated in Figure 3-3. The diagram defines different levels for the use of BIM in the construction industry. Level 0 BIM, is limited to the use of 2D CAD files for production information; the majority of design practices have used Level 0 BIM in their practices for many years. Level 1 BIM acknowledges the increased use of both 2D and 3D information in projects, while Level 2 BIM requires the production of 3D information models by all key members of the Integrated Team. However, these models need not co-exist in a single model. BIM challenges arise when moving from level 2 BIM to level 3 BIM, as defined by the creation of the single project model that allows for the harnessing of information in the model for integrated use. BIM level 3 facilitates various analytical processes and design optimisations for building performance. Within the scope of this thesis, the author explains the importance of data exchange with regard to the information needed for sustainable construction, and for sustainability compliance checking. The development of a definite method for information extraction from the BIM model offers an effective solution for dynamic sustainability compliance checking (Riba, 2012).

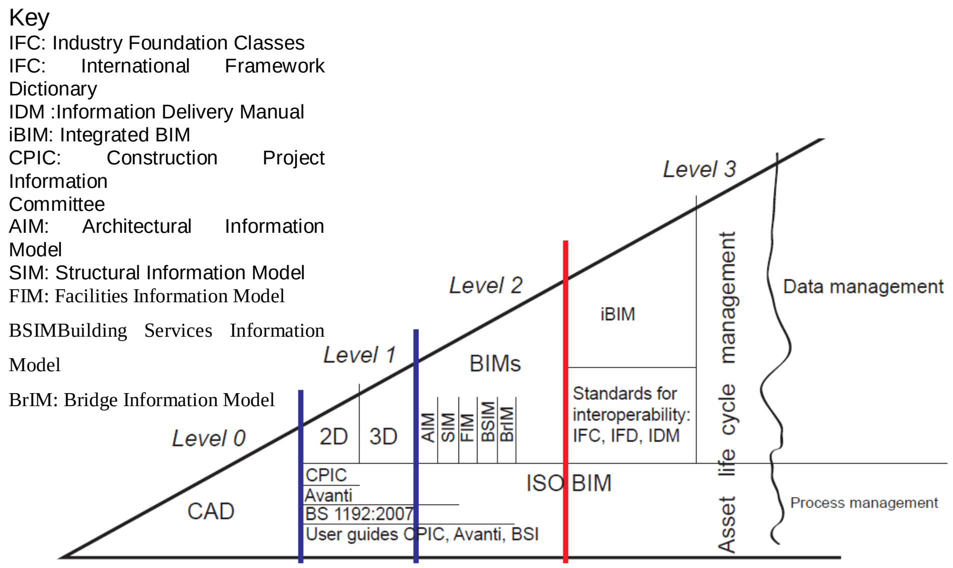

Figure 3-3 BEW/Richards BIM Maturity Scale

The central file storage mechanism for information sharing has been widely used for BIM information sharing. Subsequently, BIM data exchange methods have expanded from intra-disciplinary collaboration through specific BIM applications, to multi-disciplinary collaboration through a BIM-server. The BIM server is defined as "…a collaboration platform that maintains a repository of the building data, and allows native applications to import and export files from the database for viewing, checking, updating and modifying the data" (Singh et al., 2011). The purpose of a BIM server is to provide collaboration capabilities similar to those of document management systems (DMS). In addition, a BIM server allows for integration with embedded intelligence, by providing a multi-disciplinary collaboration platform for information exchange. A BIM server hosts the building information, and allows for collaboration between project teams; although it has limited built-in applications, it has the potential to allow a direct exchange of information between various applications involved within the construction project, such as design tools, analysis tools, a facility management system, and a document management system. The task of developing BIM servers has been of interest to many researchers; different methodologies have been summarised, and theoretical frameworks have been presented (Singh, Gu et al. 2011).

In addition to the data sharing technologies for construction information, a BIM data management scheme is crucial. With the wide range of multi-disciplinary lifecycle data available, current BIM applications have focussed on information management and extraction from the BIM model. The main issue is how to filter redundant information for specific requirements, and to extract only specific information for certain applications. There are different formats for data representation supported by software used in the AEC industries, hence, it is difficult to exchange data of different formats directly between various applications. To overcome these limitations, buildingSMART proposed Industry Foundation Classes (IFC) as an open source for exchanging data between project participants within the AEC.

3.2 Challenges and barriers to World-wide BIM adoption

With the evolution of BIM technologies, the benefits and barriers of BIM adoption have been the field of interest of many researchers, who have deployed quantitative and qualitative approaches. Han Yan and Peter Damian conducted a questionnaire survey to analyse the benefits and drawbacks of BIM. The researchers concluded that improvements are still needed in the development of BIM technology, and discussions are still required for the complete adoption of BIM in the AEC industry (Azhar et al., 2008).

BIM adoption has the potential to improve the design phase of the project. For example - from an architectural point of view - BIM can facilitate the introduction of changes at any time without any difficult processes, complex harmonisation, or manual checking work. In the construction phase, BIM also shows its power by reducing construction time, cost and overhead during the operation. Furthermore, it has a significant effect on improving the process of construction, by facilitating document and information sharing between team members. The construction industry appears optimistic about the prospects of BIM adoption.

BIM deployment has been occurring worldwide over the past few decades. Its adoption has been encouraged by many governments; in the United States, the use of BIM has been encouraged in the public sector, and the General Services Administration has developed BIM guidelines to facilitate the adoption of BIM solutions (Howard and Björk, 2008). The Norwegian Directorate of Public Construction and Property (Statsbygg) has called for all of its buildings to be BIM-compliant. Similarly, the state property services agency, Senate Properties, in Finland have demanded that BIM be adopted in all of its projects (Gu et al., 2008) (Wong et al., 2009). In the United Kingdom, the government has set a target for BIM implementation, and requires every project to be BIM-compliant by 2016 (Rezgui et al., 2013, Eadie et al., 2013, Palos et al., 2013).

BIM implementation is the target of many enterprises across the UK, because of the overwhelming benefits over the lifecycle of a construction project in terms of cost, time, quality, productivity and more. However, like all evolving technologies, BIM implementation shows some drawbacks and limitations, especially when inter-operability is required between multiple models and tools (Grilo and Jardim-Goncalves, 2010). Inter-operability is the ability to work on the same model while conducting different activities and addressing several requirements at the same time. Working on different aspects of a project, such as energy analysis, structural design and HVAC simulations, results in multiple data models which need to be analogous to eventually achieve a single comprehensive BIM model. This issue has not been solved yet, since different software tools use different data formats (Eastman et al., 2008a). Nevertheless, these issues are likely to be solved by IT companies supplying BIM solutions.

Furthermore, there are several legal issues related to copyright and model ownership, liability and responsibility of information sharing (Thompson and Miner, 2007). More importantly, when a BIM is adopted by a construction company, the design team need to be trained to a certain level to overcome the complexity of the BIM implementation.

3.3 BIM Implementation

3.3.1 BIM tools and usability

BIM repositories of project information are populated using BIM authoring tools, which use object-oriented parametric modelling systems to present the building’s information. This means that every individual object within the BIM model is constrained by rules to determine their entity and behaviour (Eastman et al., 2011). There are a diverse range of BIM authoring tools used to generate different parts of the BIM model for different domains of the design; for example, a ‘BIM architectural model’ presents the architectural features of the design, while a ‘BIM structural model’ comprises the structural behaviour of building objects. The ultimate benefit of BIM is achieved when multiple design models are integrated in an inter-operable way, allowing data sharing within an 'integrated BIM model'. There are a number of commonly-used BIM authoring tools produced by well-known competitive BIM solution providers. Solution providers are continuously making efforts to achieve the optimum functionality of the produced tools.

The current solutions are labelled as relatively stable and safe for deployment. However, most of the available tools are lacking in some way, and are still facing limitations regarding their wider adoption (Barlish and Sullivan, 2012). Autodesk (Autodesk, 2014) has been recognised as the leading construction software developer in the world; it has developed ‘Autodesk Revit’, which is a coherent, inter-operable collaboration system for BIM across the whole construction project. Autodesk Revit comprises the Autodesk Revit Architecture, which is inter-operable with Autodesk Revit Structure and Autodesk Revit MEP (Mechanical, Electrical and Plumbing). This development sets a platform where the designers from different domains can efficiently work on a shared BIM database.

This platform is known as the ‘Revit BIM platform’, which allows for interference control and greater coordination, since an electronic notification is sent to the design team whenever a change is made to the BIM model. In addition to providing BIM modelling capabilities for different domains, Autodesk Revit solutions have excellent features for sharing the model with energy analysis and simulation tools (Khemlani, 2004), and an IFC model can be automatically generated and exported to other tools for further analysis. Although the developers are making great efforts to improve the function of data sharing, there are still some limitations related to errors and lost data (Howell and Batcheler, 2005).

Autodesk solutions can also share IFC with other BIM authoring tools, such as Bentley Systems (Bentley, 2014); they are of the biggest mainstream construction software developers in the world, providing solutions for the building, plant, civil and geospatial vertical markets, in the areas of architecture, engineering, construction (AEC) and operations. This is done through a list of tools that includes Bentley Microstation – Architecture, Structural, Civil, Mechanical, Electrical, AutoPIPE, HVAC, & Facilities, Tri Forma and Factory CAD. The previously-listed software packages offer tools from drawing and modelling capacities to design rules reviews.

In addition, Google SketchUp (SketchUpBIM, 2012) also provides the features of 3D modelling, but also attaches information to each object. Although Google SketchUp possesses excellent features in terms of its easy user interface, data sharing and integration with other software tools, it has limitations in providing parametric design features, and therefore has not been labelled as a ‘BIM tool’ by (Malin, 2007). Other BIM platforms used for design and construction include the ‘Tekla’ (Tekla, 2014) tool, which is described as providing an accurate, detailed and data-rich 3D environment for the building and construction industry disciplines to share. This tool possesses ideal features for consulting and presenting a modelled structure of construction data at any stage of the project lifecycle. Tekla BIM has the capability to link with various systems through ‘Tekla Open API’ (application programming interface); this API is implemented using Microsoft.net technology. Tekla BIM supports various standard formats including IFC, SDNF, CIS/2, and DSTV, and proprietary formats including DGN, DWG and DXF. Similarly, Innovaya (Innovaya, 2010) is one of the new software providers that emerged during the BIM boom. The features of Innovaya solutions focus on the inter-operability issues within the BIM environment, and specifically between Autodesk solutions and other construction software or MS Project. Other BIM platforms and tools are summarised by (Eastman et al., 2011). BIM software companies such as Bentley Systems, Autodesk and Graphisoft have developed their integrated BIM solutions, where the regulation compliance checking has become a differentiating and marketing feature. This is reflected in Bentley System's AECOsim Compliance Manager (Bentley 2014); a project management and collaboration service to automate the LEED certification process for the United States Green Building Council (USGBC) (Farias 2013). The system is based on a centralised online LEED data repository, and a record of project information. The system checks a building's LEED rating using checklists, wizards and calculators. However, this state-of-the-art service falls short in providing an integrated solution that seamlessly extracts the necessary data from the BIM, taking into account the lifecycle and supply chain complexity; this is a clear gap addressed by this thesis.

3.3.2 The IFCs

The only comprehensive international standard for BIM inter-operability available so far is IFC; the IFC specification is written using the EXPRESS data definition language, and registered by the ISO (International Organization for Standardisation) as ISO16739, and is currently recognized as the mainstream standard for Open BIM (Vanlande et al., 2008). The data model has been developed and managed by buildingSMART, (Initially known as International Alliance for Inter-operability (IAI)) (Beetz et al., 2010), to facilitate data sharing between different AEC applications for better inter-operability (Fazio et al., 2007). With the re-naming of the international alliance of inter-operability *'IAI'* as *'BuilidngSmart* in 2006, a great change in the contextual business benefits of the IFC data model have been revealed. This change affirms the role of IFC in facilitating the delivery of an integrated design and construction process by *"improving communication, productivity, delivery time, cost, and quality throughout the whole building life cycle"* (Kiviniemi, 2006). The development of the IFC scope over time is summarised in Figure 3-5. With the development of IFC, its capability for inter-operability has been maximised, although the data model has increased in complexity and entanglement. Beyond geometric information, IFC intends to cover definitions that describe the consistent data representation of the entire building's components, their physical properties and relationships (Zhang and Issa).

The data structure of IFC is based on 3-D geometric models and object-oriented specifications. In spite of its complexity, IFC has been efficiently supported by more than 20 vendors (Zhiliang et al., 2011); while the richness of information offered by IFC is evident, there are still tremendous challenges in developing comprehensive representations of performance-specific information ready for extraction for direct compliance checking (Tan et al., 2010).

The IFC model generally involves an integrated model that includes substantial information regarding a BIM-based project; this information is usually generated by various project participants, therefore the size of the IFC model file increases continuously during the project's lifecycle. Consequently, importing and exporting IFC files is a difficult and time-consuming process. When any participant requires information related to their field, it is difficult to extract that information, particularly in the case of design, construction, green building, mechanical, electrical and plumbing (MEP) data. Therefore, it is more efficient to use certain IFC files containing only essential information required to carry out specific activities, rather than using the master IFC model (Lima et al., 2002). The ability of IFC schema to comply with class libraries of different applications, and to support information sharing and representation, promotes its context to be an "open industry-wide standard definition of data structures for the capture and exchange of information", rather than a commercial product for any company. The IFC format is approaching a full consensus between all stakeholders on the technical content of BIM implementation, and currently it is in the process of becoming an official international standard ISO/IS 16739 rather than ISO/PAS '*the publically available specification'*

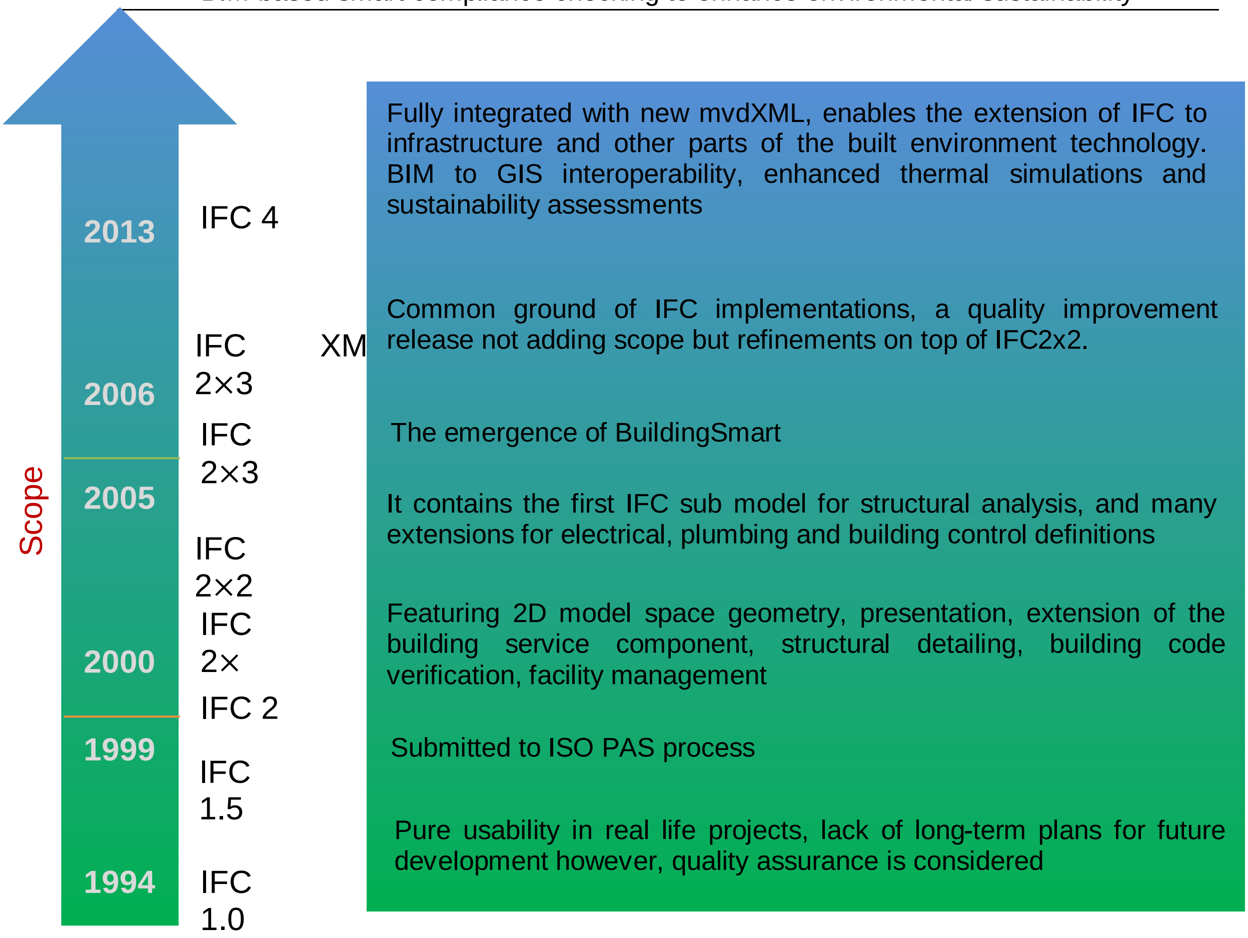

Figure 3-4 Time scale of IFC development

Within the IFC, there are a number of hierarchical, object-oriented data models formalised with the EXPRESS data modelling scheme. The EXPRESS scheme defines all entities and types of definitions, relationships and cardinality of building models. Each data model represents the data elements for every part of a building, and defines its spatial relationship; in addition the relevant information about the spatial extents is illustrated. Hence, the IFC schema is a consequence of different data models, and contains a class diagram that outlines the relationship among its entities. The class diagram is also represented by an interpretable description associated with certain constraints. This representation enables the generation of executable codes for the use of information sharing among several applications.

The architecture of IFC is split into four levels: the Domain, Inter-operability, Kernel and Resource Layers. The highest level is the Domain Layer, which contains the concepts of different domains in the AEC industry, such as management, structural elements, building controls and so on. This layer only describes the entities of a specific domain.

The second level of specification concerns the inter-operability and data exchange among applications; it is known as the Interoperability Layer, and defines the common concepts across multiple applications within the domain. For example, the data model ‘IfcSharedBuildingElements’ contains entities of common concepts such as ‘IfcWall’, ‘IfcWindow’, ‘IfcDoor’ ‘IfcSlab’ and ‘IfcFloor’.

The Kernel Layer is the third level within the architecture of the IFC, and it represents the ‘IfcKernel’ data model. It contains the core and the core extension, which defines the entities and roots for all classes defined in the highest level. The most abstract entity defined in this layer is the ‘IfcRoot’, which holds the general constructs within the kernel data model such as ‘IfcObject’, ‘IfcProperty’ and IfcRelationship .

The fourth level is the Resource Layer, which defines the properties for all resource classes used in the higher-level classes, such as quantity, time and cost. This layer consists of several data models; each data model contains predefined types which are used by the layers of the highest levels to assign values and attributes to the predefined type. For example, the data model ‘IfcGeometryResource’ contains the concepts of ‘IfcPlane’ and ‘IfcCircle’. Figure 3-6 provides the official description of these levels with reference to the buildingSMART website (buildingSMART, 2013b).

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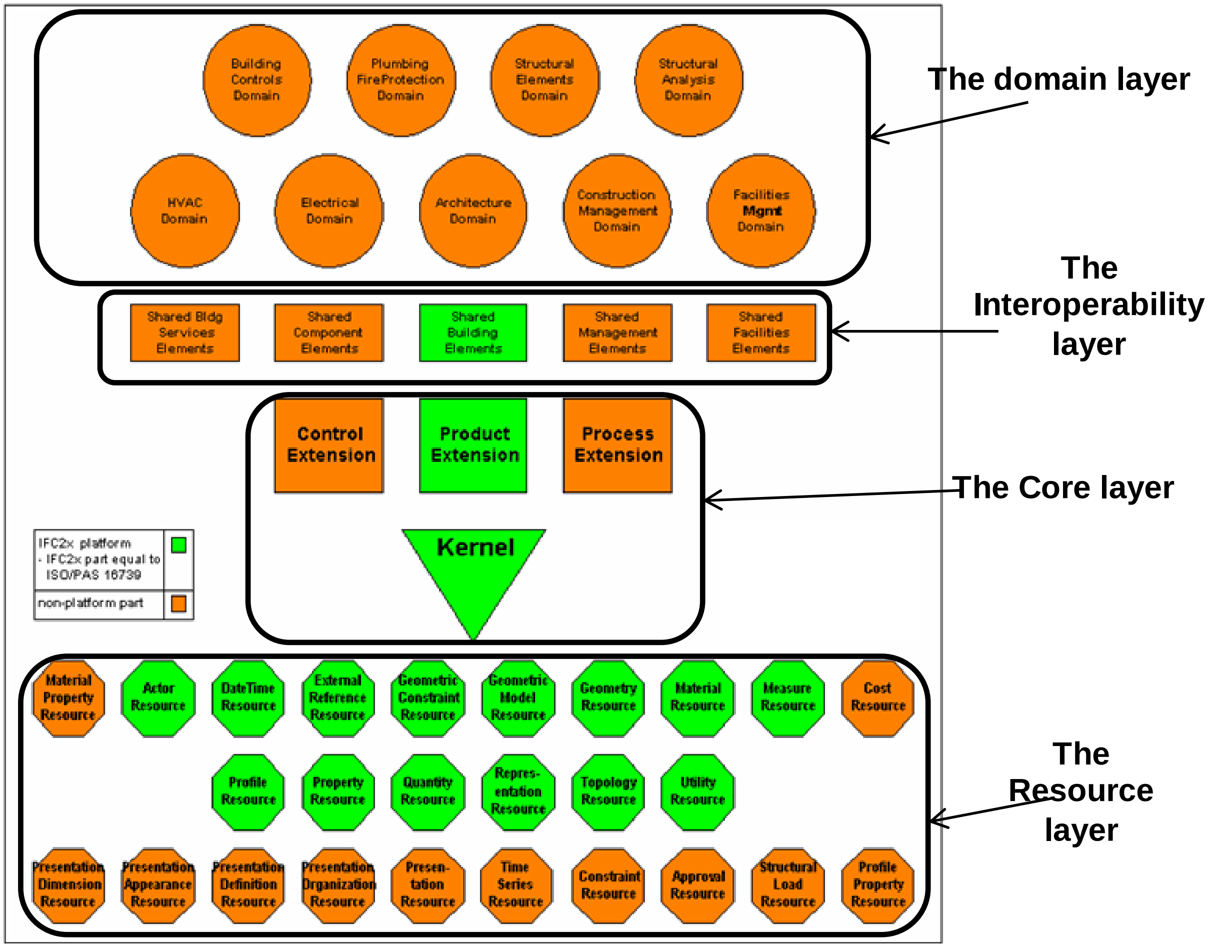

Figure 3-5 The official description of the IFC data model (buildingSMART 2013)

The development of IfcXML as an official XML representation of the IFC data model both began and was released in 2001.

XML (Extensible Markup Language) is a language for data transfer between software tools, designed to structure, store and transport data (Bray et al., 1998). The language is a self-descriptive, and is readable by both humans and computers. The basic function of XML defines a set of rules to encode documents using XML tags, and the resulting format can be transported between a sender and a receiver. XML has no predefined tags; tags must be defined by methods such as DTD (Document Type Declaration) or an external XML schema can be written using XSD (XML schema definition) (Hughes et al., 2003). XML has a global language format, with consistent syntax that can represent and translate a computational building model using the appropriate mapping engines. This allows a group of people or organisations to establish their own descriptive mark-up language to exchange information within their domain of interest -. XML supports a diversity of software tools.

Recently, many countries have begun to convert their textual legislations and regulations into XML standard format to improve retrieval and to facilitate embedding these regulations into their business process (Grandi et al., 2005). There have been considerable efforts towards developing the XML framework to express regulations (Cheng et al., 2007). These trials are crucial in converting the textual regulations into a computer-understandable format. This approach will be adopted in the current research to facilitate automated compliance checking against sustainability regulations.

The development of IfcXML as an official XML representation of the IFC data model began and was released in 2001. The methodology involves generating the XML schema definition (XSD) out of the IFC EXPRESS schema definition, using XML language bindings. The result is a written translation of IFC EXPRESS into IfcXML FORMAT.

XML presentation of the IFC data provides the opportunity to a broader community of applications to be able to access a unified data representation of the built environment (Nisbet and Liebich, 2005). There exists a vast range of supporting database implementation, web services and utility applications of XML schema. XML represents the basis of most web services and e-commerce(Liebich, 2001), in particular, with the support of XSLT (Extensible Style sheet Language Transformations) for transforming XML files into different formats such as plain text, HyperText Markup Language (HTML) for web pages and so on, which could be further converted into Portable Document Format (PDF). Through adhering to the enriched IFC contents and the semantic XML, the AEC-FM industry can benefit from an internationally agreed standard form BIM data sharing, based-upon the existing standards in several domains using different representations(Taylor, 2001). The conceptual challenges of translating a modelling language do not always result in an instant solution to the conceptual context. For example, the translation of native IFC-STEP into IfcXML results in unwanted data, data loss and un-optimised files, due to the inherently-different structures of XML models and the STEP file. The current release is ‘ifcXML4’, which is published as an XSD, derived from the IFC EXPRESS model. The translation method of the IFC EXPRESS model into the ifcXML XSD model is based on the international standard ISO 10303-28 "XML representation of EXPRESS schemas and data" (Siltanen and Pärnänen, 2006). Table 3.1 compares an example of the original IFC EXPRESS definition and the generated IfcXML schema following the ISO 10303-28 international standard.

Table 3-1 IFC EXPRESS VS ifcXML

Original IFC EXPRESS definition example	ifcXML schema (generated by ISO 10303-28)
ENTITY IfcProperty ABSTRACT SUPERTYPE OF (ONEOF (IfcComplexProperty ,IfcSimpleProperty)); Name : IfcIdentifier; Description : OPTIONAL IfcText; END_ENTITY;	**<xs:element name="IfcProperty" type="ifc:IfcProperty" abstract="true" substitutionGroup="ex:Entity" nillable="true"/> <xs:complexType name="IfcProperty" abstract="true"> <xs:complexContent> <xs:extension base="ex:Entity"> <xs:sequence> <xs:element name="Name" type="ifc:IfcIdentifier"/> <xs:element name="Description" type="ifc:IfcText" nillable="true" minOccurs="0"/> </xs:sequence> </xs:extension> </xs:complexContent> </xs:complexType>**

3.3.3 gb XML

The term gbXML refers to the green building XML schema, which was developed to facilitate the transfer of information from the BIM model to the energy analysis and simulation tools, and benefits from export/import capabilities in several green building tools within the construction industry (Attia and De Herde, 2011). Furthermore, it has become the de-facto standard format supported and adopted by most of the commercial BIM applications such as Autodesk solutions, Bentley, and Graphisoft (Barnaby, 2008). In addition to its contribution to achieving energy-efficient, sustainable buildings, gbXML supports collaboratively-integrated design, and utilises the benefits of BIM. Although the IFC data model comprises a plethora of data needed for energy simulations, gbXML is commonly-used for representing and transferring energy-related data; (Dong et al., 2007) described it as the preferred schema for most of the energy simulation tools. There are a number of research studies and practical applications published in the literature concerning the inter-operability of BIM with energy simulation tools. Most of the reported implementations utilise the import/ export features of gbXML and IFC data, however a seamless integration has not yet been achieved; there are some issues in the data transfer format that constrain the data transfer. Some of these issues have already been identified by (Osello et al., 2011), who compared the IFC and gbXML data exportation through two case studies employing Revit Architecture and Revit MEP with Ecotect and IES<VE> simulation environment. The researchers remark that, in both cases, the data transfer process exhibits reoccurring changes to the original architectural model, and that iterative manual editing of incorrectly-imported geometry is needed to achieve the desired results. However, it has been reported that the gbXML schema is far more capable in exporting energy and lighting data than the IFC, because of the latter's limitations in representing the data needed for energy analysis and design. Unlike other domains (the structural analysis domain, HVAC domain…etc.), the energy analysis domain needs to be added to the IFC schema. A general statement that can be made at this point that it is difficult to extract and transfer detailed information for green design, and specifically for energy analysis among design tools (Hamza and Horne, 2007).

In this thesis, the IFC data model will be used for data transfer between the BIM tool and compliance checking system. Also, due to the inability of IFC to sufficiently represent energy-related data together with the plethora of sustainability compliance requirements data, a roadmap for a sustainability-domain-compliant IFC is proposed.

3.4 BIM Based Compliance Checking Solutions

A general definition of compliance is “the conformance to a rule, such as a policy, specification, standard, or a law” (Burby et al., 1998). Regulatory compliance describes the obligations that associations or public agencies need to undertake to comply with relevant standards (Breaux et al., 2006). Recently, regulatory compliance has become more prominent in the construction sector; due to the increasing number and complexity of regulations, organizations for compliance professionals are seeking integrated and harmonized approaches to control compliance with operational transparency (Hardy, 2006); their ultimate aim is to ensure that all government requirements are met without the need for the unnecessary duplication of efforts and investment. The automated compliance checking of building performance and construction operations has received little attention due to the complexity of the structure of construction-related data. Until recently, the only way to handle the growing body of complex knowledge generated by construction processes was human cognition. Although some computerized analyses such as structural analysis have become critical to the design process, there are still essential aspects that continue to be dealt with manually (e.g. details of safety factors). The emergence of BIM presents an opportunity to support the 3-D object modelling, and initiates a new era for automated compliance checking systems. Further to the parametric design that complies with various criteria, BIM allows the establishment of computer-interpretable design models with automated checking features(Martins and Monteiro, 2013).

Compliance checking systems are defined as software that assesses a building according to a configuration of objects, attributes and their relations. They apply rules or conditions to test if the building design complies with these rules. Rules checking systems do not modify the design, but rather, report the results in the form of “pass”, “fail”, or give a warning for wrong or missing data.

The development of rule checking systems is evolving, and their application is expected to move beyond code checking at the abstract level of the building design, to examining detailed aspects of the design, and eventually to become a standard tool used throughout the life-cycle of a construction project. Rule-based checking systems can have various implementation platforms, for example: 1) a stand-alone application that runs on desktops parallel to the design-generating software, 2) a web-based system that can check designs generated by various sources, or 3) a compliance checking application that is attached to a design tool as a ‘plug-in’. Such applications would allow for constant checks throughout the design development phase - each of these systems has its own merits and drawbacks. Current efforts have focused on developing a generic desktop-based compliance checking system. The rule-based system is then integrated in the form of a plug-in with an industry standard design package.

Most of the compliance checking solutions utilize Industry Foundation Classes (IFC) to facilitate data exchange (Maissa et al., 2002). IFC is the only neutral data model that represents a building for compliance checking (Wix et al., 2008). The IFC system supports most BIM design tools in information sharing and representation, and it is currently known as the mainstream standard for Open BIM (Vanlande et al., 2008). Nevertheless, it has limitations in representing all of the information for compliance checking requirements.

The efforts reviewed in this thesis utilise IFC, and the author also relies on the IFC data model in the current development. Nevertheless, the efforts focus on expanding the scope of the current data model by adding a set of properties that enhance the IFC to be compatible with compliance requirements.

This Section gives an overview of Regulatory Compliance Checking Solutions, highlighting four phases of the development process (a rule interpretation phase, a building model preparation phase, a rule execution phase, and a rule checking and reporting phase). Section 3 reviews the currently-available platforms for compliance checking: the Solibri Model Checker (SMC), Jotne ED model checker, FRONAX and SMARTcodes. The current applications have been criticised in Section 4 and a comparison among these systems is given in Section 5, to define the areas with drawbacks that will be addressed in the new development.

3.4.1 Overview on compliance checking systems

Existing regulatory compliance checking solutions have previously functioned by applying rules to IFC models (Liebich et al., 2011). The rule checking process is separated into four phases, as illustrated in Figure 3-7: a Rule Interpretation phase, a Building Model Preparation phase, a Rule Execution phase, and a Rule Checking and Reporting phase (Eastman et al., 2009b). Several compliance checking systems, such as CORENET-Singapore, Norwegian Statsbygg's design rule checking efforts, the International Code Council (ICC), and general services administration design rule checking (GSA), have already been implemented However, these systems still have limitations in terms of inter-operability (Tan et al., 2010), For example, the information for compliance checking requirements is not compatible with the information within the IFC file, or in many cases some compliance checking requirements are not even available within the information model in the first place (Tanyer and Aouad, 2005).

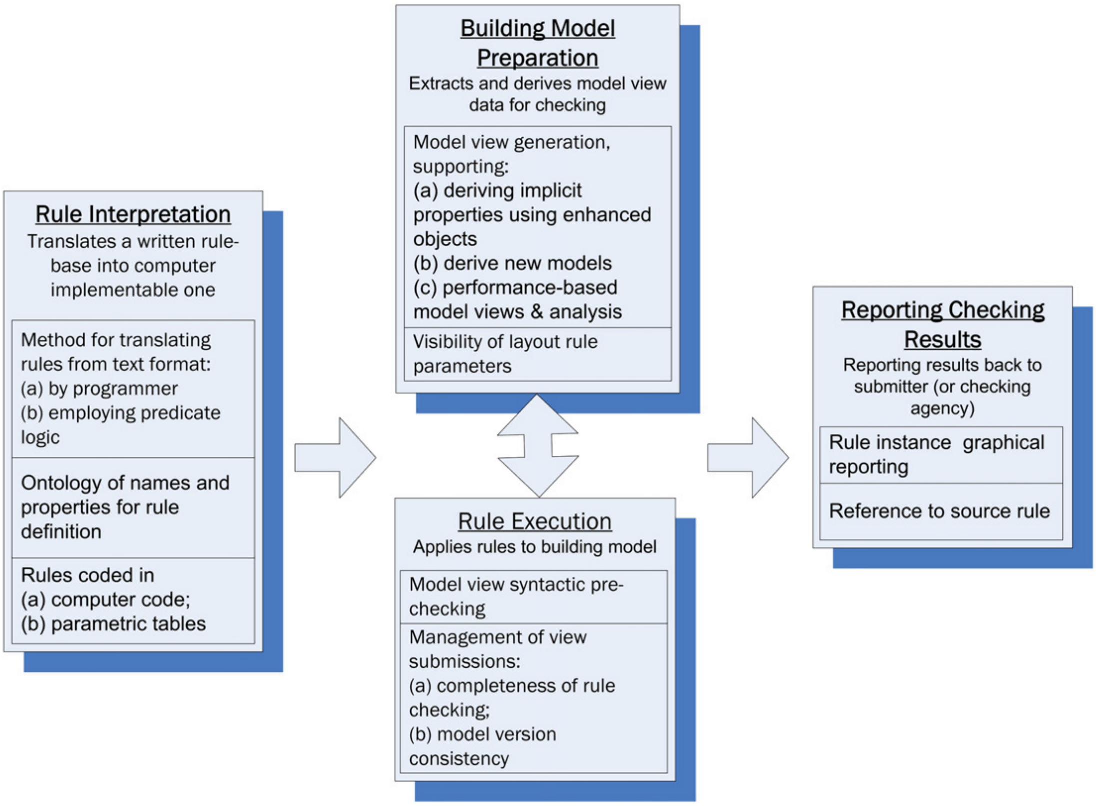

Figure 3-6 The four classes of functionality a rule checking system (Eastman, Lee et al. 2009)

3.4.2 Platforms for compliance checking

The development of rules-based checking systems started in the last two decades (Han et al., 2002). However, the application of actual compliance checking systems is just beginning to become possible, since the technologies are still young and evolving rapidly. At present, there is no comprehensive solution that provides full functionality for an automated regulatory compliance checking system. In this thesis, four platforms for rules-based checking systems are reviewed; all of them are applying rules to the IFC data of a building model to check the building's compliance against these rules.

3.4.2.1 Solibri Model Checker

The most-recognized platform of compliance checking is Solibri Model Checker (SMC), the main purpose of which is to achieve continuous quality control for the BIM model during its life cycle. It has an intuitive walk-in functionality to examine the design features and capture clashes. With SMC, the IFC files from different BIM models, such as from architects, M&E, Structures and so on, are combined together and the check is then run on the combined model to assess the overall quality, and to reveal potential flaws and weaknesses.

SMC is a Java-based desktop platform, with identified rule sets that are used for model checking. The functionality of SMC is based on an information take-off (ITO) capability, which allows users to collect information from the BIM, organise it, visualize it, read the IFC file, map it to its rules structure, and report results instantly. The information that can be checked with SMC includes areas and spatial calculations, the envelope of the building to be used for energy calculations, volumes, and quantities.

In SMC, users can specify - for example - what requirements for the minimum thickness, length, and height of the walls, the ratio of the window area to the floor area of spaces, the maximum allowable distance of any space to the nearest exit when checking for valid escape routes, and the allowable overlaps when checking for intersections between any two types of components. The use of SMC is limited to quantitative information within the design, where a simple algorithm based on topological relationships is applied.

3.4.2.2 Jotne Express Data Manager EDM ModelChecker

Another platform for compliance checking is the Jotne EDM ModelChecker (EDM). The EDM platform is open and sophisticated; it provides an object-based database, where a programmer is needed to translate the written rules into a computer code. The rule is coded using express language, and the EXPRESS-X Rule schema. EDM targets checking accessibility by using IFC model properties and relations, and the internal model for defining access. The platform is supported by the EDM Model Server, which is an object-based database server that provides an effective way to deal with large building models and/or multiple models at a time. This platform has been adopted in Australia in the Cooperative Research Centre for Construction Innovation (CRC-CI). The Norwegian Statsbygg's design rule checking efforts have adopted EDM, together with the multiple platforms SMC and E-plan Check to conduct design rule checking based on actual building projects (Eastman et al., 2009b).

3.4.2.3 FRONAX

The Singaporean CORNETE project for the E-plan Check created its own platform known as 'FRONAX'. This platform is a C++ object library, based on IFC data. The basis of the FORNAX schema is to extend the IFC information to include the information needed for compliance checking with certain building codes (Nawari, 2012). FORNAX captures rules' semantics, and has functions to retrieve properties from IFC objects, depending on the type of rule. This platform is adopted to check building services against related building codes, including rules dealing with building control, access, fire codes, vehicle parking, and ventilation.

3.4.2.4 SMARTcodes

SMARTcodes is a new platform for compliance checking. Its functionality is based on translating the rules from written language to computer codes, using a dictionary of terms of specific domains and mapping methods. This platform is developed by AEC3 and Digital Alchemy (AEC3, 2012).

SMARTcodes has been implemented together with SMC, for building code check efforts by International code council ICC USA.

3.4.3 Rules based model checking efforts

In this section, some implementations of rule checking systems are summarised. Most of these implementations are still developing, and have not yet been public. This review is based on published scientific papers and technical reports.

3.4.3.1 CORENET-Singapore

Construction and Real Estate NETwork (CORENET) was the earliest of the code checking efforts; it was established by the Ministry of National Development in Singapore in 1995 (government, 2008). The CORENET project consists of three modules for the design phase: CORENET e-Submission, CORENET e-PlanCheck, and CORENET e-Info.

The e-Plan check is the relevant part to the review in this thesis, at the early stages of the CORENET project initiation, the electronic drawings were used for compliance checking, but, in 1998, the IFC was introduced as the data source for compliance checking. The aim of this project is to check the building plan and building services against the relevant codes. The building plan is checked against rules dealing with access, fire safety, health and safety and vehicle parking. The building service compliance check includes rules of electrical distribution, fire alarm systems, and the distribution systems such as gas, pipes, ventilation water and drainage systems; the compliance check is based on the configuration of these systems (W.Soilhin, 2004). The CORENET project developed a semantic library in FORNAX to include both rules definitions and IFC extensions, for certain entities for the compliance check. Each object in the FORNAX library has diverse functions to retrieve the needed properties from IFC. It has been reported that the CORENET rules can be hard-coded in computer programming languages and that the FORNAX software library needs full computer programming capacity to structure a rule writing system for a particular requirement. Nevertheless, a programmer is not needed to develop algorithms for retrieving the data needed from IFC (Eastman et al., 2009b). The CORENET Singapore effort in code compliance checking was the earliest-known development in the field, is currently the furthest deployed. More than 2500 firms within the construction sector in Singapore are currently using the CORENET system to submit their plans to the government (government, 2008).

3.4.3.2 Norwegian Statsbygg's design rule checking

As an effort by the European countries to explore the possibility of utilising BIM for automated compliance checking, the CORENET e-plan check system was implemented in the Akershus University Hospital project, to check design accessibility dimensions related to evacuation rules; this implementation paved the way for early Norwegian efforts in design rule checking systems. The Norwegian Agency of Public Construction and Property (Statsbygg's) rule checking system has been further developed, focussing on spatial requirements checking, building accessibility checking and other processes defined by IFC (Eberg et al., 2006). This system was implemented by Tromsø University College (HITOS); the design model was prepared using BIM tools, and included detailed definitions of all main building elements. The design team ensured that the BIM model included sufficient data for compliance requirements (ISO, 2011), and the design was checked using the Solibri Model Checker (SMC) platform. When the IFC model is prepared, SMC retrieves all of the relevant rules associated with building objects and their geometric data. Hence, the system maps these data with the required values coded in the compliance checking equations defined by SMC. There are some rules developed specifically for the HITOS project; Statsbygg announced that implementing the SMC could reduce the common design failure and deficiency by 60-70% (Statsbygg, 2006).

3.4.3.3 Australia Cooperative research centre for construction innovation design check

The Australian Building Codes Board (ABCB) on behalf of the Australian Government takes the responsibility of maintaining and updating the Building Code of Australia (BCA). The board initiated an effort to automate accessibility compliance checking. Both Solibri Model Checker (SMC) and Express Data Manager (EDM) were examined for accessibility checking which are defined in the BCA D3, Australian Standard (AS) 1428.1 “Design for access and mobility”. The object oriented approach is followed for the design check implementation. A pre-implementation specification structure of performance requirement, objects, properties, and relationships was applied. The written statements of performance requirements is extracted from the building code and then translated into computer code (by people). The translated performance criteria are then translated into objects, properties and relationships to facilitate handling. The EDModel checker utilises the EXPRESS language to define the rukes schema. Since all the objects, properties and relationships utilised by the rules are defined in the IFC, the rules schema definition becomes clear.This specification structure facilitates the generation of a coded description for performance requirements. To facilitate executing the rules, the ABCB-EDM system is organized into groups of rule sets. A chosen rule set run against the BIM model initially to check if all the required information is provided then the final compliance checking is run.

3.4.3.4 International Code Council (ICC)

The international code council (ICC) adopted a new approach for rule checking systems based on SMARTcodes. The development of SMARTcodes was carried out by AEC3 and digital alchemy (AEC3, 2012), and was supported by the ICC. They provide a digital version of regulations by mapping the written codes into computer-processible code sets. The rules are encoded in the ISO standard EXPRESS-X language. The aim of developing SMARTcodes was to facilitate automated compliance checking against ICC regulations. They were first implemented in the International Energy Conservation Code (IECC) (Council, 2006a). The SMARTCodes define all IECC-critical objects for compliance checking, also to define their properties, in order to generate an IECC dictionary. The dictionary does not only interpret the rules, but it also communicates with the IFC building model. The SMC system is used for compliance checking, by mapping the building model data to the SMARTcode dictionary via a web-based application. The web-service requires the building model to be uploaded in addition to some input data such as the building location and the code to be tested against. Currently, only pre-configured test models are implemented, where the compliance checking requirements are provided to satisfy the compliance checking process (council, 2012).

3.4.3.5 General services administration design rule checking (GSA)

The US General Services Administration (GSA) initiated the national 3D-4D program. Since 2007, all new construction projects were required to submit BIM data allowing for spatial validation and automated design guide checking. These requirements include data of area measurements, and building efficiency measurements such as the fenestration ratio. When the design model is submitted for compliance checking, a quick analysis is conducted by the GSA team initially. Various area calculations are defined by the code of practice; these area values are automatically derived from the BIM model according to pre-defined calculation procedures for space calculation methods. The assessment is done using SMC, similar to that used by Statsbygg, but it uses different methods for area calculation. The GSA also applies the same method for rule checking of circulation systems and security validation. The rules are extracted from Courts Design Guide (CDG) in the United States. The entire guide was digitally scanned, and only the relevant statements for compliance checking were identified. Over 300 statements were analysed and grouped into sets of similar conditions. These statements were then translated into computer-understandable coded statements. The circulation rules were parameterized into four level conditions: 1) Start Space, 2) Intermediate Space, 3) Destination Space and 4) Transition Space. Each level has a specific name and security restrictions (public, restricted or secure). These condition levels present distances, vertical accessibility, and dimensions as specified by the SMC system. As soon as the BIM model includes the data that satisfies the compliance checking requirements defined by SMC, the assessment is conducted via a plug-in developed by the Georgia Institute of Technology (Eastman et al., 2009b) .

3.5 Conclusion

Building information modelling has been designed to achieve interoperability in the construction sector. Its implementation has been deployed world- wide and is developing rapidly within the industry. The principle of interoperability is based on information exchange between participants from different domains within a construction project. To enable interoperability BIM implementation is standardised by IFC schema for the data exchange. The IFC data model comprises the taxonomy for the conceptual representation of the BIM data. BIM concepts are well structured and formatted in a way that is both human and machine readable to achieve interoperability. The IFC data model is defined by EXPRESS and XML. However, most of the BIM applications adopt IFC XML as a standard format for the data exchange. The IFC has been labelled as a rich data model but can be redundant. This redundancy imposes anarchy during the data sharing and results in huge, error prone files. To overcome this issue, MVDs have been developed to extract a subset of IFC for a particular domain. The aim of this chapter is to search for the challenges that need to be addressed to achieve seamless automated sustainability compliance checking through interoperability between BIM and sustainability regulations. Although the latest release (IFC4) promotes full integration with new mvdXML, it enables the extension of IFC to the infrastructure and other parts of the built environment technology and promotes enhanced sustainability assessment, The state of the art review falls short in providing an integrated solution that seamlessly extracts the necessary data for sustainability compliance checking from the BIM, taking into account the lifecycle and supply chain complexity. Since the UK government has stressed the need for an efficient construction industry which encompasses the principles of sustainability as an inherent matter, the RIBA has complied with this and has developed a new generation of ‘RIBA Plan of Work’ that incorporates the principles of sustainable design and provides the infrastructure for BIM involvement aiming to contribute to the transformation of the construction sector. The involvement of sustainability compliance checking is an embedded process alongside the BIM implementation through the work flow of a construction project and is still in its early stages. There is still a need to precisely address the challenges of such implementations.The methodology applied in the aforementioned compliance checking approaches was to create IFC models with one of the BIM software systems such as Autodesk Revit architecture, Bentley, Google Sketch Up or ArchiCAD and then process the IFC files to facilitate information exchanging and processing (Salama and El-Gohary, 2011). Most of the previous developments focused on the architectural and structural design domain, where efforts were exploited only to examine compliance with relatively simple form of rules such as dealing with geometrical or special attributes (Khemlani, 2002). For example, checking access dimensions, doors sizes, or wall thickness (Yang and Xu, 2004). Existing tools lack the capability of performing logical compliance checking such as checking compliance with contractual requirement, quality control and the construction’s safety procedures where the information is not semantically represented in the BIM model. Table 3-2 summarise the current features of the four major code compliance checking systems with reference to the compliance checking process stages defined by (Eastman et al., 2009b)

	CORENET	Statsbygg	ABCB	(ICC)	(GSA)
Rules Interpretation					
Target rules	Building code	Accessibility	Accessibility	Building code	Circulation and security
platform	FORNAX	SMC	EDM	SMART CODE	SMC
Writing rules to computer code	Programmers or person predicate logic derivation process	Programmer	programmer	programmer	programmer
Rules generation	Computer code	Parametric tables	Express rules schema	Smart codes	Parametric tables
Incorporate reasoning in data extraction	No	No	No	No	Space name based ontology
Building model preparation					
Derive new properties using enhanced objects	FORNAX new properties	SMC library	Sub-model schema includes new properties	Smart codes library	SMC library
Derive new models	No	Performance model view	No	No	No
Rules execution					
Map data between dictionary and IFC	Only check the explicit definitions in IFC	Only check the explicit definitions in IFC	Only check the explicit definitions in IFC	Only check the explicit definitions in IFC	Only check the explicit definitions in IFC
Rules check reporting					
Results visualization	no information available in the literature	Graphical reports after the check visualised in 3D design	Graphical reports after the check not inked to 3D design	Graphical reports after the check visualised in 3D design	Graphical reports after the check visualised in 3D design
Clash detection	no information available in the literature	Visualised clash detection	no information available in the literature	no information available in the literature	Visualised clash detection
Design tool linkage	Not linked to design tools	Not linked to design tools	no information available in the literature		Not linked to design tools
Allow for dynamic design check	The tool works separately new design can be checked constantly	Reports failures and recommend amendments for the design	no information available in the literature	no information available in the literature	Reports failures and recommend amendments

The features of the current compliance checking solutions underpin the fundamentals for the development of a BIM-based sustainability compliance checking system. This development will be introduced in the following chapters of this thesis. The development presents a move from the vague and limited applications of the current solutions, to a transparent and comprehensive end-to-end methodology, which is applicable in various domains of knowledge.

Chapter 4

Methodology for Regulatory Compliance Checking System

4.1 Introduction

The term research refers to a search for knowledge; the English Advanced Learner's Dictionary defines research as "a careful investigation or enquiry, especially through the search for new facts in any branch of knowledge" (Wehmeier and Hornby, 2000). Similarly, (Redman and Mory, 1923) defined research as "systematized efforts to gain new knowledge". Research, furthermore, relies on a series of systematic methods, and begins by defining and refining problems, and ends by achieving solutions. Hence, from the problem definition to the problem solution, multiple proceedings occur; hypothesis formulation, data collection, data organising and analysis, and evaluation to reach certain results and conclusions.

Returning to the hypothesis/question posed at the beginning of the study, this chapter will discuss the research methodology applied to answer the research questions. In this chapter, the different types of research methodologies will be discussed, to justify the approach that was selected for this study.

This chapter will begin by stating the motivation in research, outlining what makes people undertake research, and summarises the motivation for the current research. A review of the dominant basic types of research will be given, followed by a summary of two main research approaches; the *‘quantitative’* approach and the *‘qualitative’* approach. In this chapter, the significance of various research into providing guidelines for solving different social, business and governmental problems will be discussed.

The primary purpose of this chapter is to introduce the research methodology. Hence, various research methods versus methodologies will be described, followed by explaining the research design and methodology, which provides a systematic method for answering the current research questions.

4.2 Research methodology

There are multiple aspects that motivate undertaking the current research. Firstly, the increasing complexity of building regulations and the rapidly-evolving requirements are causing the assessment of building compliance to become a technically complex, rigorous and costly process (Cole, 2005). In addition, with the advent of new technologies, the design of buildings, and related construction practices, have changed dramatically. Buildings have become more sophisticated, and possess increasingly-complex inter-related systems (Krygiel and Nies, 2008). Hence, building regulatory compliance checking is becoming rather more challenging.

The purpose of this research is to contribute to the original knowledge, contributing to its advancement by applying scientific procedures to answer the research questions. Although each research study has a specified purpose, the overall goal of the studies is to construct a new system that automates regulatory compliance checking.

Therefore, this research has been initiated to take advantage of the currently-evolving BIM technologies to establish a method for automating the highly-complex and technically rigorous regulation assessment process.

There exist several attempts to do this, discussed in chapter two of this thesis. Nevertheless, it has been found that there is currently no unique comprehensive compliance checking system which has been ultimately adopted in the construction sector.
The current research involves studying the configuration of information within a targeted regulation, with the aim of developing a sophisticated information system for automated compliance checking. It is therefore necessary to understand the nature of information systems that constitute appropriate research in that area.

Information systems research is a multi-perspective discipline, and therefore it can incorporate a plurality of research methods (Baskerville and Wood-Harper, 1998). The domain of information systems incorporates scientific, engineering, technological, managerial, and societal aspects. Currently, the discipline of human-computer interaction is prominent, highlighting the role of end users and expanding the discipline to incorporate physiology, linguistics, sociology and philosophy, in addition to graphical design, marketing and engineering. The evolving technologies has pushed the information systems into diverse domains(Wood-Harper et al., 1985). Previous research has indicated that information systems are 'maturing science', and that much of the current information systems research is fragmented, lacking theory and methods. Such research does not fit neatly into a positivist paradigm, in particular when qualitative methods are used (Boudreau et al., 2001). Information systems are an area that is largely based upon empirical studies, that investigate the qualities of the information itself. Such is the case, for example, with enquiries into management decisions and social processes.

An implication of these findings is drawn from the information system research domain; a constructive approach was chosen for the current research, where a research problem has been identified, and research questions were formulated accordingly, in order to achieve the research objectives (Kasanen et al., 1993; Lukka, 2003; 2006) that comprises the following Stages:

1. Orientation consisting of identification of the problem, organisation of the project, identification of aims and objectives and conducting a literature review.

2. Design involving the construction of an artefact (software).

3. Evaluation consisting implementation and assessment of the artefact.

4. Dissemination incorporating reflection on the applicability and generalisation of the artefact and identification of the theoretical contribution of the project.

The deductive research approach includes various stages, beginning with the identification of the problem, followed by the production of the theoretical framework, where the research hypothesis is identified. According to this hypothesis, a list of research questions is identified, in order to formulate the constructs, concepts and operational definitions. Based on these definitions, the research is designed to incorporate the collection of the research data through the literature review, data analysis and interpretation, in order to develop the new information system. This system is then validated through two case studies. Figure 4-3 illustrates the research approach for the current study.

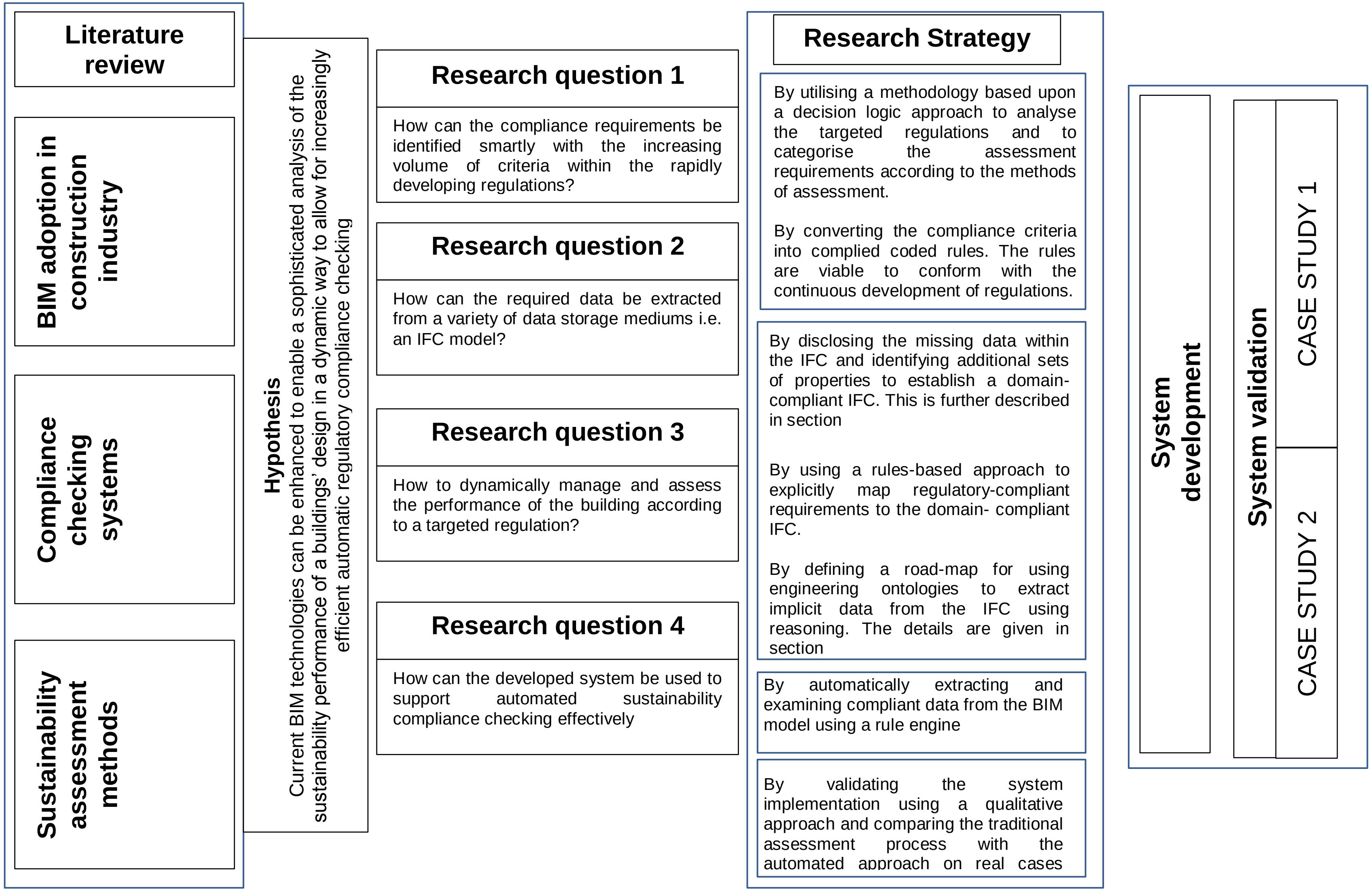

Figure 4-1 The research approach

The choice of the research approach is normally associated with research objectives. At the same time, it is also influenced by the available resources such as time, skills and available data.

In this research, an intensive literature review has been conducted to investigate the currently-available sustainability compliance checking systems. The literature review covered three major topics. The first topic was the currently-adopted environmental assessment methods and rating systems in the construction industry. Different approaches, frameworks and methodologies for environmental assessment methods were examined, with a focus on the BREEAM assessment method. Environmental performance standards and regulations were also investigated, together with the technologies and tools for sustainability performance analysis. It has been found that the contribution of these technologies is limited, because of the amount of data, time and effort which they require, and the associated cost. It has therefore been concluded that the current environmental assessment methods are inefficient. Although pre-design assessments are usually conducted, improving non-compliance issues at the later stages of the construction requires significant investment, time and efforts. The available environmental rating systems aim to motivate high-quality design, construction, and operation, in order to achieve high performance. This conclusion has led to the formulation of the first research question of this thesis; “How can the compliance requirements be identified smartly within the context of rapidly-developing regulations and an increasing volume of criteria”.

The second part of the literature review focuses on information management in the construction industry, and the evolution of BIM technologies. This part of the literature review investigated the current collaboration and interoperability state of BIM. BIM technologies and information sharing methods were investigated, with a critical review of the IFC data schema. The information exchange technologies throughout the design process were examined, and the subsets of IFC information to meet certain requirements were examined. Furthermore, this thesis investigated the possibility for MVD development for sustainability compliance checking. This part of the literature review led to the formulation of the second research question “How can the required data be extracted from a variety of data storage media, i.e. an IFC model".

Within the same chapter, the third part of the literature review focuses on bringing together environmental sustainability compliance requirements and BIM interoperability, as a means of facilitating the development of a sophisticated compliance checking system. This part of the literature review focussed on investigating the existing work in the field of regulatory compliance checking, with a focus on sustainability-related issues in the AEC sector; this is found in Chapter 3 where the current principles, methodologies, platforms and available solutions are critically summarised. It was concluded that the methodology applied in the existing compliance checking systems focuses on the architectural and structural design domain, where efforts were exploited only to examine compliance with relatively simple rules, such as dealing with geometrical or spatial attributes (Khemlani 2002), for example, checking access dimensions, door sizes, or wall thickness (Yang and Xu 2004). Existing tools lack the capability of performing logical compliance checking, such as with contractual requirements, quality control and the construction's safety procedures, where the information is not semantically represented in the BIM model. This part of the literature review led to the formulation of the third research question; "How to dynamically manage and assess the performance of the building according to a targeted regulation"

The literature review has provided a comprehensive set of data for the analysis to approach the research objectives. It can be stated that both qualitative and quantitative approaches were followed for gathering the information for the current research. It has been concluded that the current textual documents of the standards and regulations currently used by industry were not originally designed for automated processing (Kasim et al., 2012b). Based on this analysis, a system has been developed by the researcher, to automate the process of compliance checking by converting the regulatory statements into machine-readable rules, and using the rules engine to process these rules for compliance checking solutions.

In the final stage, the hypothesis will be tested using two case studies, The Monument pilot project and the Orthopaedic hospital design. The first case study includes empirical BREEAM Assessment for the non- residential case studies. The Monument pilot project was used to implement the developed tool on an existing project, without having the capability to manipulate and amend the model according to the requirements of the compliance checking tool; this project is currently under construction. The pragmatic IFC was used to examine the current coverage scope and the required level of details for automated compliance checking. A more detailed validation has been conducted using the Orthopaedic hospital design (In Revit software). For this case, the designers and the author interacted during the validation phase, to assist with resolving issues arising regarding the model, IFC and level of details required. The holistic BREEAM assessment has been conducted both manually and using the developed system, and the comparison between the two approaches has been discussed.

4.3 Significance of Research

“Research is the fountain of knowledge for the sake of knowledge and an important source of providing guidelines for solving different business, government and social problems.”(Weiss, 1977). The significance of research in diverse fields promotes the development of logical habits of thinking and organisation. For example, within the fields of business and applied economics, the increasingly-complex nature of business and government corroborates the roles of research in solving operational problems. The role of research has greatly increased in modern times, and has gained added importance when it drives the development of policies for both business and government; in fact, nearly all government policies are based on research findings (Bozeman, 2000).

Through research, the consequences of these policies are constantly examined, and alternative policies are sought. Decision making may not be undertaken through research; nevertheless, research certainly facilitates the decisions of policy makers.

Three major contemporary issues have motivated this study. Firstly, in 2011, the UK government announced that the use of Building Information Modelling (BIM) will be mandatory for all public-sector projects from 2016 (Counsell, 2012). This announcement has formed a basis for research topics for BIM adoption strategies. The employment of BIM technologies are evolving rapidly; existing BIM technologies, however, are either inappropriate for widespread adoption, or incapable of supporting the Government's environmental agenda.

The emerging BIM technologies aim to achieve financial benefit and improved carbon performance, through the use of open sharable asset information. This constitutes the second motivator for investigating the potential of BIM to facilitate sustainability assessment, energy performance and carbon footprint measurement in buildings. It has been found from the literature review that the current sustainability assessment methods are not efficient, and that involving the BIM concept within the sustainability assessment process would be beneficial.

The current research has been initiated in accordance with UK government strategy on adopting BIM technologies and achieving compliance with standards and regulations.

The construction industry requires an innovative, and comprehensive compliance checking system enhances the assessment process which is currently expensive and time-consuming. If the BIM modelling concept is used during the early stages of design, design teams will be able to manipulate and modify their work to achieve the desired performance. In adopting modern BIM technologies, accompanied by some technical improvements, designers can perform parametric studies to analyse and visualise building performance, and also perform a detailed and precise building simulation and an energy performance analysis. However, in order to feasibly conduct these analyses in the early design and pre-construction stages, comprehensive yet accessible sets of information and knowledge regarding building form are needed.

BIM stores the entire building information in an integrated parametric database, which can be used to perform the analysis of many aspects of the design process, however, the full benefit of integrating it with sustainability assessment systems needs to be critically investigated. In particular, some technical barriers exist related to the data exchange within the BIM environment, which sometimes limits the exploitation of BIM technologies.

The information required to support the environmental assessment process is currently fragmented across domains, and not ready to be used as guidance to a designer or be accessible within a software-based design environment. Furthermore, there is potential that real-time performance can be dynamically monitored as the design proceeds. It can be concluded that the current work is applied research that may have a significant impact in the construction sector.

4.3.1 Formulating the Research Problem

The definition of the research problem is the key to a research project. The formulation of research problem starts by developing a general understanding of the area of research interest. A researcher needs to gather relevant generic subject matters. At the early stages of the research, the stated research problem may be found to be very broad, with lots of ambiguities. Gradually, these ambiguities will be resolved as the research proceeds.

Before formulating the research problem, the researcher must also study the feasibility of the solution. Once the researcher has ensured that the solution is obtainable, the formulation of the research problem can be set up. The formulation of a specific research problem from a general topic constitutes the first step of the scientific enquiry. Essentially, formulating the research problem involves two steps, as stated by (Kothari, 2004); ”Understanding the problem thoroughly” and ”rephrasing the same into meaningful terms for the analytical point of view”

The current research has been initiated by investigating the availability of sophisticated methods for achieving sustainable construction. Several environmental assessment methods and rating systems were searched, and smart assessment methods were sought. Further to this, the emergence of BIM technologies in the construction sector was investigated, with the aim of defining advanced methods for presenting construction information assets. The generalized research field was then narrowed to cover two main topics; ‘*sustainability assessment methods’* and ‘*Building information modelling’*. The author has undertaken intensive searches to examine both the conceptual and empirical literature. The author looked for concepts and theories that have the potential to be further employed. The empirical literature has been investigated to determine whether a similar study within the same context has been previously conducted. The outcome of the literature review was the development of a comprehensive knowledge, and an examination of the available resources to specify the research problem in a meaningful context. It has been concluded that there is lack of BIM to support environmental assessment methods and rating systems, and there is the potential for developing a sophisticated compliance checking system that streamlines the process of checking a buildings' sustainability performance.

4.3.2 Extensive literature survey

After formulating the research problem, an intensive literature review has been conducted to provide an increased understanding of the research topic, and to support a process of conceptualising the essential related research parameters. This stage of the research is critical for identifying the major aspects related to the research topic, and to determine the main variables that have an impact on the research problem. The literature review also aids in evaluating the different aspects in relation to relevant studies in several research domains, such as an environmental sustainability domain, regulatory compliance policies, and information systems. Appropriate factors and measurements were identified to support the theoretical framework development of the current study.

The literature review revealed two topics that are especially important in the present study. Firstly, the traditional methods of conducting regulatory compliance checking of buildings are criticised for their deficiency (Gupta and Dantsiou, 2013). These criticisms signal a major shift to a new covenant in setting up the regulations to meet the modern era. Changes in building design and operations have been occurring continuously; the processes are becoming more ICT (information communications technology)-oriented; in the face of such trends, legislation, standards and regulations need to change accordingly. The traditional textual presentation of compliance requirements needs to be transformed into more logical expressions of their content - this issue forms one component of the current research.

The second topic to highlight in this section concerns the current adoption of Building Information Modelling (BIM), which has been designed to achieve interoperability in the construction sector. Its implementation has been deployed world-wide, and is still developing rapidly within a competitive industry. The principle of inter-operability is based on information exchange between participants from different domains within a construction project. To enable inter-operability, BIM implementation is standardised by an IFC schema for the data exchange. The IFC data model comprises the taxonomy of a conceptual representation of the BIM data. BIM concepts are well structured, and formatted in a way that is both human and machine readable, to achieve inter-operability. The IFC has been labelled as a rich data model, but can be redundant. This redundancy imposes anarchy during the data sharing, and results in huge files which are error-prone. The state of the art review falls short in providing an integrated solution that seamlessly extracts the necessary data for sustainability compliance checking from the BIM, taking into account the lifecycle and supply chain complexity.

It can be concluded that there is an urgent need for a methodology to enable dynamic requirement checking as a designer designs their building; this issue will be addressed in the rest of this thesis. The involvement of sustainability compliance checking is an embedded process, alongside the BIM implementation through the workflow of a construction project, and is still in its early stages. There remains a need to precisely address the challenges of such implementations. The literature review highlighted that the ultimate benefit of sustainability compliance checking can be achieved when the targeted regulation is converted into more precise, explicit logical expressions, these rules embedded into the compliance checking environment, and the building performance simulation tools integrated with compliance checking tools. This will result in a more efficient solution with lower cost and minimised effort involved in automatically checking building sustainability compliance. The findings of the literature review were used to developing the working hypothesis, developing the data analysis method, and defining the research design development methods.

4.3.3 Development of Working Hypothesis

A research hypothesis can be defined as a statement created by researchers when they speculate upon the outcome of a research or experiment. A research hypothesis is a tentative assumption formulated to draw out and test the logical or empirical consequences of the research activities. Therefore, the manner in which the research hypothesis and the research questions are developed is particularly important, since they provide the focal point of the study. In most types of research, the working hypothesis is essential; it provides the guidelines for the researcher by delimiting the area of the research, sharpening the researcher's thinking, and indicating the types of data that are required and the types and methods of data analysis to be used. For the research hypothesis to be scientifically accepted, it needs to be tested and validated, and the feasibility of the research methodology must be approved.

The current research has been initiated by the definition of the research statement that seeks a solution for an existing research problem. Based on this hypothesis, four research questions were identified to examine the possibility of developing an efficient automatic regulatory compliance checking solution. The research methodology has been identified as the optimal method to answer the research questions. The required data has been defined, and data analysis tools and technologies have been adopted. A generic system for compliance checking has been developed accordingly, and the system implementation has been validated using a qualitative approach, and by comparing the traditional assessment process with the automated approach using real-world cases studies.

4.3.4 Information and data gathering

Collecting the appropriate data is essential for the research process. Based on the information obtained, the researcher plans the next stages of the research to find an appropriate method for data analysis. In the current research, a plan was agreed for data gathering - details are given in Table 4.1. This plan is based on several questions; (1) Why was data collected? (2) What was the research strategy in relation to data collection? (3) What were the data sources? (4) How was the data gathered/collected? (5) How can the data collection findings be concluded? In the current research, the data mainly obtained from the literature review. Nevertheless, different websites were sought, and meetings with experts in the field were also conducted, in order to evaluate the literature review findings against the practically-implemented procedures, and to identify the gap for the current research. It has been found that the current environmental assessment process involves only limited implementation of automated processes, in particular for energy performance modelling, and that the role of BIM to facilitate compliance checking is currently rudimentary.

Table 4-1 Information gathering plan

Question	Information gathering plan
Why was data collected	**Sustainability compliance checking** • To gain a comprehensive understanding of the context of the information handled during the sustainability assessment process of building performance. • To understand the nature of assessment criteria and the relevant data required to meet each criterion • To define the different sources and measures of the data requirements **BIM** • To understand the current adoption of BIM to facilitate sustainability compliance checking • To investigate the current data asset of Building information modelling • To examine the possibility of promoting BIM data to include the requirements for sustainability compliance checking.
What was the research strategy in relation to data collection	• Analysis of text documents, government policies, and relevant regulations • Conduct qualitative and quantitative methods for data analysis • Convert the textual documents into digital formats • Embed the converted data into the BIM environment
What were the data sources	• Interviews were conducted amongst BREEAM assessors, regulatory developers, BIM experts and experts in the relevant area. • Sustainability regulations manuals and approved documents including '*BREEAM', 'Code for sustainable home'* and '*English building regulations'* • Internet sites relevant to this research including BuildingSMART, RIBA, BRE,..etc. • Books, published articles, white papers and best practice.
How was the data gathered/ collected	• Textual analysis including content analysis of policies and documents. • Analysis to the data collected via internet sources and through published articles.
Data collection finding	Data is measured in a different way according to the assessment criteria. • Information provided by the users • Data obtained by applying some procedure to available data • Data calculated by external application • Data provided from external • BIM data standard IFC is currently redundant however, it has a Lack in presenting data requirements for sustainability assessment.

4.3.5 Conceptual framework development

Based on the gathered data, several stages were incorporated to develop the conceptual framework for automatic compliance checking system development. This stage involved different approaches and technologies to achieve the desired output. The first stage involves data analysis and categorization to define the appropriate method for dealing with the data.

Figure 4-5 illustrates the overall structure of the conceptual development of the rules-based approach.

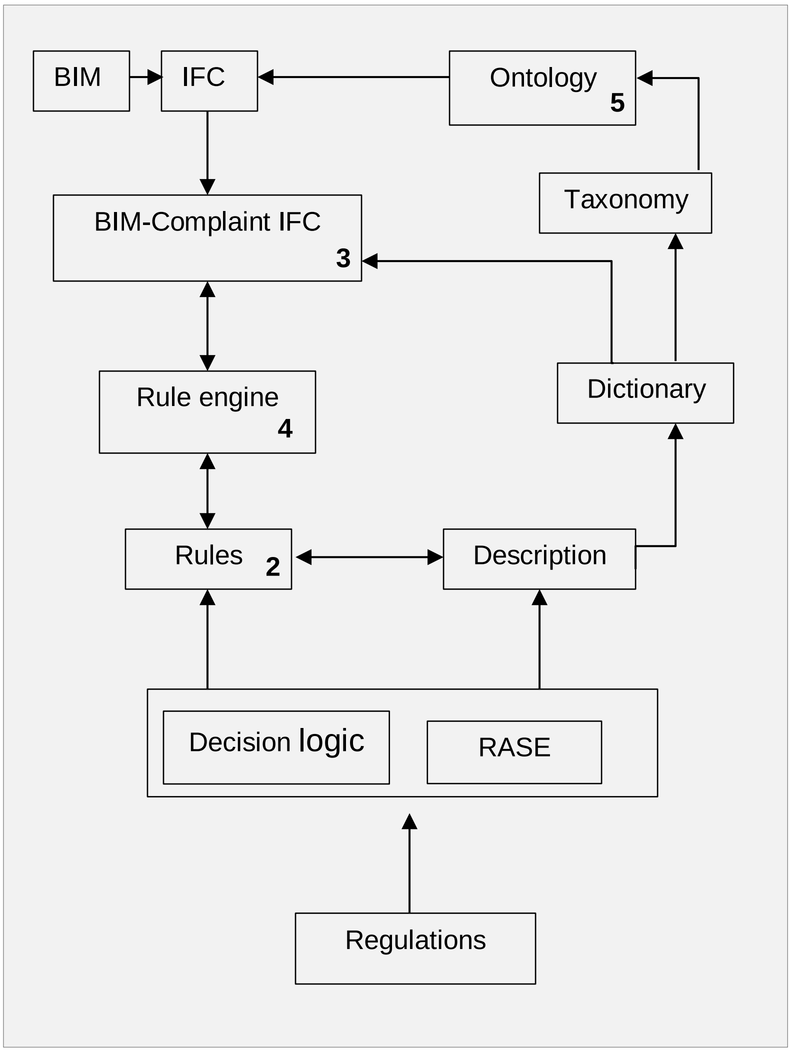

Figure 4-2 Conceptual developments for compliance checking

Figure 4-5 shows the stages of converting standards into rules to facilitate compliance checking. Within Figure 4-5, Label (1) shows how rules are extracted using decision logic and a metadata language called RASE (Hjelseth and Nisbet, 2011). This process creates formalized business rules that can be further-integrated into automated services, as shown in Label (2). The output of this process is a taxonomy of the domain of compliance requirements, and their required data for a particular regulation. This taxonomy describes all objects and attributes that are needed for the assessment.

Based on this taxonomy, a list of data items has been identified, to generate a dictionary of compliance data requirements. The advantage of having this dictionary is to perform an enhancement of the current IFC standards (Label 3). From this analysis, a set of improvements have been identified in order to make an IFC extension for sustainability compliance checking. The concept of engineering ontology has also been employed in the current development as an alternative method for mapping the regulatory data with the IFC, through the establishment of the data taxonomy (Label 5). Finally; a rule engine is used to perform the compliance check against an IFC model (Label 4).

4.3.6 Data analysis

Data analysis is a process of inspecting the data with the goal of understanding its nature. The process of data analysis has multiple facets and approaches encompassing diverse techniques in different domains. In the current research, data adopted by the textual regulatory documents is addressed, which the building compliance needs to be checked against, and represents the data asset of the BIM model.

To understand the context of the regulatory textual data, the regulations concerning building sustainability were inspected. These are the 'English building regulations', 'Code for sustainable homes' and 'BREEAM'. These regulations comprise all of the criteria for environmentally-sustainable constructions that buildings need to comply with. It has been found that the currently-adopted versions of these regulations and standards have not been designed in a way to be handled automatically. The textual diversified descriptions of the requirements textual format of these standards and regulations were not originally designed for automated processing (Kasim et al., 2012b). Some texts present an explicit and logical description of a single criterion, so these expressions can be dealt with directly; on other occasions, there are several explicit criteria included in one statement. In such cases, the information within the statement needs to be separated first, to serve the individual logical criterion for each requirement. Furthermore, many regulations comprise implicit - and hence complicated - criteria which can only be judged by human professionals (Antoniou et al., 2005). In order to automatically embed the compliance checking in a design environment, the compliance requirement needs to be converted into logical expressions (Munda, 2005). The regulatory data also need to be categorized according to the type of data – i.e. whether it is quantitative or subjective data. The details of regulatory data analysis will be explained in detail in Section 5.2 of this thesis. As a result of this stage, a list of the data required for sustainability compliance checking has been developed, to ascertain their compatibility with the data of the BIM model as part of achieving the integration of regulatory and BIM data.

BIM data were also inspected with the aim of understanding the current BIM asset, and investigating how much data concerning buildings' sustainability features is currently adopted by the BIM data model (IFC).

The IFC data model comprises the taxonomy of the conceptual representation of the BIM data. BIM concepts are well-structured, and formatted in a way that is both human- and machine-readable, in order to achieve inter-operability. The IFC has been labelled as a rich data model but can be redundant. Nevertheless, the IFC lack representation of most of the information relevant to the buildings' sustainability features and it needs to be extended to cover new subsets of data requirements; the details of this process will be further explained in Section 6.2 of this thesis.

4.3.7 Processing data using Decision logic and RASE operators

To facilitate processing the descriptive regulatory requirements for our automated compliance check solution, the complicated and nested criteria of the regulations have been re-organized in logical expressions using conditional logical trees. A conditional logical tree has been generated for each set of sub-criteria using the features logical spreadsheet. Each individual decision statement has been placed in a cell within a decision spreadsheet. Every decision has been viewed as having a series of sub tests that must be satisfied. This is done by adding additional metadata to the regulation in a process called “Marking Up” using RASE operators ‘Requirement, ‘Applicability’, ‘Selection’ and ‘Exemption’. This process of marking up allows the addition of extra semantic information to the regulation. Further details will be given in section 6.3 of this thesis.

4.3.8 Rules execution and Drools the rules engine

To process the decision spreadsheets and the RASE meta-data that has been added to the individual cells within the spreadsheets, a rule engine has been used for this purpose, named DROOLS. In order for the DROOLS rule engine to process the data, the spreadsheets and meta-data must be converted into a format understandable by the rule engine (Community, 2013). This conversion is done by using a rule compiler, which converts textual rules into DRL (DROOLS rule engine language), by utilizing a series of logical formulas based on the decision spreadsheets and the RASE tags within the cells of the spreadsheets. Further details will be provided in Section 6.4 of this thesis. Section 6.5 then focuses on system implementation, where defined sets of regulatory requirements are mapped into the IFC data, and the implementation findings discussed. This stage reveals the challenging obstacles of applying a rules-based approach to automate sustainability compliance checking. The rules generation depends on the complexity of the original regulatory statements. As a result of this stage, a sub-set of data requirements for the sustainability features of buildings have been defined as an area for IFC extension.

4.3.9 Ontologies

By adopting the rules-based approach for automated compliance checking, the regulatory constraint statements have been modelled as simple strings. However, this leaves space for many mistakes in editing the constraints; for example, it is possible to define a constraint statement and not to declare all variables in the statement. In order to overcome this shortcoming, and to support the exchange of constraints between different engineering tools, a more formal approach to modelling the constraints statements can be chosen. The concepts of engineering ontologies have therefore been used in this research; by using the ontological frame representation, the sustainability compliance checking domain can be enriched by extending and harnessing the knowledge with additional axioms, which can be interpreted by a logical reasoning; this will contribute to a powerful automated system with minimal user engagement. The details of ontology implementations will be discussed in Chapter 8 of this thesis, practical examples of implementations will be provided.

4.3.10 Hypothesis Testing and Validation

The last stage of the methodology includes hypothesis testing and validation. Every stage of the current development has been verified to answer the final research question, and to demonstrate that the developed solution effectively supports automated sustainability compliance checking. To provide a solid validation for the system, the section concerning validation has been split into four expanded sub–sections; ‘validating the extraction of decision logic from regulation documents’, validating the conversion of decision logic into computer-executable rules’, and ‘verifying the system’s effectiveness through two case studies’. For the purposes of consistency, BREEAM was employed as the environmental assessment method for both case studies. For the purposes of describing the process, all of the illustrations given are based specifically on BREEAM Pollution Issue 01 (Impact of refrigerants).

The case studies used in this thesis are the Monument Pilot Project and Orthopaedic Hospital Design. The chosen case studies were designed using different BIM tools - Bentley and Revit. The Monument Pilot Project' was provided by Skanska UK Ltd (Skanska, 2014), while the 'Orthopaedic Hospital Design Project' was provided by a group of research students at Cardiff University, and was verified by Arup Ltd. (Arup, 2014). The two projects were used as real-world cases in order to prove the validity of the developed tool.

The un-modified Monument Pilot Project was used to implement the developed tool with a real project, without having the capability to manipulate and amend the model according to the requirements of the compliance checking tool - this project is currently under construction. The pragmatic IFC was used to examine the current coverage scope, and the required level of details for automated compliance checking.

A more detailed validation has been conducted using the Orthopaedic Hospital Design, using the Revit software. For this case, the designers and the author interacted during the validation phase, to assist with resolving issues arising regarding the model, IFC and level of details required. The holistic BREEAM assessment has been conducted both manually and using the developed tool and a comparison has been discussed.

4.4 Conclusion

This chapter introduces a methodology for developing an integrated solution to enhancing automated regulatory checking within the construction industry. The methodology applied in our research is based on existing BIM technologies, its integration of pre-existing technologies (RASE and DROOLS) are expanded with additional technologies (Semantic Dictionary and the Rules Compiler). The novelty of our approach comes from the integration of existing technologies, new technologies with the focus of providing an integrated approach to allow construction domain users to specify a regulatory compliance system without the need for software programming experience. This has now been specifically addressed in the next chapter. To the best of the researcher's knowledge, there exists no prior research in this area. Thus, the research design of this study tries to benefit from related research design in the relevant field of technology adoption studies aiming aimed at promoting sophisticated methods of compliance checking.

Chapter 5

Development Of Rules- Based System To Enhance Automated Regulatory Checking

This Chapter describe the research development methodology in details. The analysis of the targeted regulations will be given in Section 5.2. The conversion from textual regulation into logical expressions is explained in Section 5.3. Section 5.4 focuses on rules generation and execution, and the overall process is concluded in Section 5.5.

5.0 Introduction

This chapter contains a comprehensive presentation of the rule-based compliance checking system that is proposed in this thesis. In the proposed system, all regulatory requirements of the data are stored in a dedicated dictionary, making it possible to access all of the information needed for compliance checking. The currently-introduced system paves the way for a more general regulatory-compliant design management approach. It can be used iteratively to simulate the performance criteria against targeted regulations as the design develops. This helps designers to manage the compliance checking process over the life cycle of the construction project, and equally the tool provides the designer with constant feedback on how to improve the performance of the design as needed. Figure 5-1 summarises the current features of the four major code compliance checking systems, with reference to the compliance checking process stages defined by (Eastman et al., 2009b).

The stages of compliance checking described in this thesis are in line with the previously-reported efforts by (Eastman et al., 2009b), where code compliance checking is structured into four major phases: (a) Rule interpretation and logical structuring, (b) Building model preparation, (c) Rule execution, and (d) Reporting of checking results. However, there are some significant differences in terms of the functional issues presented in each phase. Figure 5-1 bridges the steps of our development with these four phases.

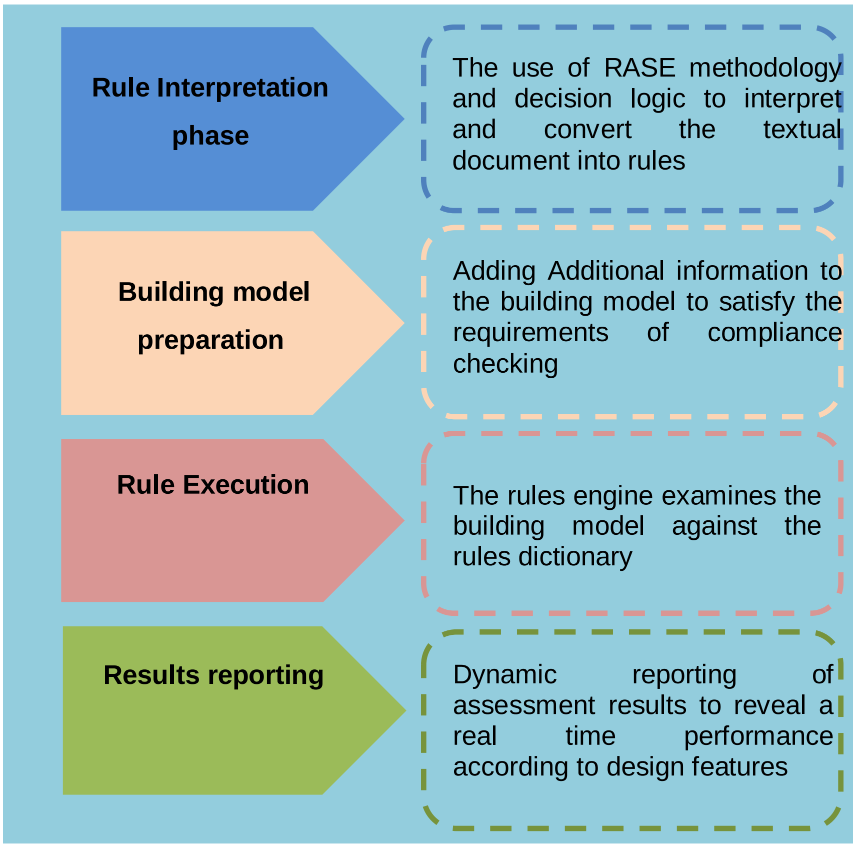

Figure 5-1 Four phases of compliance checking systems

5.1 Analysis of targeted regulations

In order to embed the compliance checking automatically in a design environment, the compliance requirements need to be converted into logical expressions (Munda, 2005). However, these regulations comprise diversified descriptions of requirements in textual format. Some texts present an explicit and logical description of a single criterion, so these expressions can be dealt with directly; on other occasions, there are several explicit criteria included in one statement. In such cases, the information within the statement firstly needs to be separated, in order to serve the individual logical criterion for each requirement. Nonetheless, many regulations comprise implicit - and hence complicated - criteria, which can only be judged by human professionals (Antoniou et al., 2005).

The methodology presented in this thesis provides a generic approach for converting assessment criteria from regulation textual documents into logical expressions. The BREEAM regulation has been used as the 'target Regulation' for the current research. The current approach has also been applied to other regulations, such as '*Code of sustainable home'* and '*English building regulations'*, to examine the applicability of different contexts of regulations. However, all of the illustrative examples provided in this chapter are based on the BREEAM assessment method.

Every environmental assessment issue covered in BREEAM is measured in a different way, according to the assessment criteria.

a) Information provided by the user, for example the number of occupants in the building or whether an operated appliance is in.
b) Data obtained by applying some procedure to available data (areas, volumes and enumerations)
c) Data calculated by external application (energy and water consumption).
d) Data provided from external sources (weather and geological data of the site)
e) Information assessed by other relevant standards (standards for lighting design and noise assessment).

There are a considerable number of subjective definitions of assessment criteria. An example is given in figure 5-2 (Global, 2011a); the assessment of such criteria cannot be achieved by relying solely on software tools through automated processes; human interaction is required to proceed with the assessment. The role of the assessors is fundamental in order to judge compliance with such requirements (Holmes and Hudson, 2003).

Either
The openable window area in each occupied space is equivalent to 5% of the gross internal floor area of that room/floor plate. For room/floor plates between 7m -15m depth, the openable window area is on opposite sides and evenly distributed across the area to promote adequate cross-ventilation
Hea7-1

Figure 5-2 Process of HEA 7-1 evaluation in BREEAM

Some assessment criteria have ambiguous definitions. The compliance requirement is implicitly embedded within the nested statements, which are only understandable by professionals with the relevant knowledge in the domain. In these cases, valid and reliable logical computer rules cannot be expressed. Figure 5-3 illustrates an example of ambiguous criteria (Global, 2011a).

Or
The design demonstrates (by calculation, using ventilation design tool types recommended by CIBSE AM1017) that the natural ventilation strategy provides adequate cross flow of air to maintain required thermal comfort conditions and ventilation rates.
Hea7-2

Figure 5-3 Process of HEA 7-2 evaluation in BREEAM

There are an overwhelming number of assessment criteria which require compliance with a strategy or sub-regulation within the regulations. BREEAM credits are only awarded if the design complies with these sub-regulations. For example, the assessment of energy performance is associated with illumination design specified by the Chartered Institution of Building Services Engineers guide (CIBSE).

Some assessment criteria correlate with the results of a professional consultation. For instance, BREEAM credits are only awarded when a relevant specialist is appointed or a professional body is consulted, regarding some design and construction features. Similarly, credits may be awarded if a reliable feasibility study is undertaken on the design at some particular stage which needs to be demonstrated with evidence (Barlow, 2011); for example, the assessment of some of Management (Man) sub-categories, as illustrated in Figure 5-4.

Man01: Sustainable procurement: one credit can be awarded where a specialist commissioning manager is appointed during RIBA Design Stages C–E to provide commissioning advice on the commissioning of complex systems that could affect the design and construction programme.

Man05: Life-cycle costs and service life planning: up to three credits can be awarded, with the first credit relating to this Issue awarded if a life-cycle cost analysis is undertaken on the design during RIBA Stages C(Concept) or D (Design Development). Further credits can be awarded depending on the scope of the analysis and whether it is updated during RIBA Stages D (Design Development) or E (Technical Design).

Figure 5-4 Process of Man 01, Man 05 evaluation in BREEAM

The assessment requirements demonstrated in the previous examples concerning Management issues (Man) do not represent objective properties of the design features. Therefore, it is not possible to determine the relevant BREEAM assessment data from a BIM model. In this case, a BREEAM assessor needs to gather the information required, together with related evidence from the construction management team, in order to conduct the assessment.

Most of the Materials (Mat) sub-categories are assessed according to construction materials specifications, their sustainability, and their robustness. Principally, a BIM model provides information about the materials specification attached to each construction object. Nevertheless, the required data may not necessarily be presented to comply with BREEAM requirements. Furthermore, BREEAM assessment of construction materials is obtained from the MAT materials specification calculator, which assesses the responsible sourcing of materials such as ‘bricks, concrete, plaster...,etc.’ comprising the main building elements such as ‘floors, walls, roofs and external building elements’. The proposed checking system relies on the ‘green guide of specification’ as a benchmark for the sustainability level of construction materials, in the form of a ‘tier level’. There is significant potential to embed the current ‘Mat calculator tool’ within BIM environment, to directly obtain the construction material specification according to BREEAM requirements (Kawazu et al., 2005). However, when a building element consists of several different materials such as external wall (brick, blockwork and cavity wall), then each material must be considered during the assessment, based on the achieved level of responsible sourcing ‘*i.e. tier level’*, and relative BREEAM credits awarded. Figure 5-5 outlines an example of a Health and well-being issue (*Mat04*).

Mat04: Insulation: up to two credits can be awarded in relation to this Issue. The first credit is awarded where the insulation specified in the following achieves an overall Insulation Index equal to or greater than 2:

- *external walls*
- *ground floors*
- *roofs*
- *building services.*

The Insulation Index is calculated by the BREEAM Assessor using a Mat04: Insulation calculator tool based on the insulations':

- *volumes*
- *thermal resistances*
- *Green Guide to Specification ratings*

The second credit is awarded where at least 80 per cent, by volume, of the insulation specified
is responsibly sourced and certified in accordance with the requirements for either Tier Levels 1, 2, 3, 4 or 5 as described for Issue Mat03: Responsible sourcing of materials.

Figure 5-5 Process of Mat 04 evaluation in BREEAM

The architectural design features of the building, such as building type, location and orientation, can be assessed directly according to BIM data. There is a plethora of BREEAM assessment issues concerning the architectural features of building design; Figure 5-6 outlines an example of the Health and well-being issue (Hea).

Hea01: Visual comfort (Daylighting criterion): either one or two credits can be awarded, depending on the building type. It is important that the design features that influence whether or not a building will achieve the required daylight performance standards for credits to be awarded are understood and incorporated from RIBA Stage C (Concept) onwards.

Hea02: Indoor air quality (Potential for natural ventilation criterion): one credit can be awarded where a building is designed so that fresh air can be provided by a natural ventilation strategy.

Figure 5-6 Process of Hea 01, Hea 02 evaluation in BREEAM

The performance of a building, in terms of its architectural design features such as natural ventilation, daylight, and building envelope, can be evaluated using building simulation tools, and the integration of BIM with building simulation tools has been achieved. The assessment of some requirements of the LEED rating system and part L of the Building Regulations is currently embedded in '*Integrated Environmental Solutions virtual reality'* IES <VR>, where the latter had been integrated with the Revit BIM tool. Embedding BREEAM requirements into building simulation tools can facilitate BREEAM assessment; this can be achieved when the assessment requirements of architectural design features are explicitly quantified to comply with building simulation results.

Equally, the energy performance of buildings can be evaluated using energy simulation tools according to BREEAM requirements (Ng et al., 2013). Figure 5-7 presents the current procedure to evaluate building energy performance according to BREEAM requirements. The procedures comprise calculation of the energy consumption, energy demand and CO_2 emissions. These parameters can be acquired from energy analysis and simulation tools at the initial stages of design; this part of compliance checking can therefore be done automatically, if the system integrates with energy simulation tools.

No. of Credits available:	*15*
Minimum standards:	*Yes*

Assessment criteria

Assessment criteria	***Description and Assumption***	***Satisfaction***	***Credits achieved***
	Requires calculation of Energy Performance Ratio for New Constructions (EPR_{NC}), then calculate credits according to the EPR_{NC} benchmark scale	*YES*	*10*

to demonstrate compliance with the available BREEAM credits, it is required to calculate the EPR_{NC} which takes account of the following parameters;

a. *The building's operational energy demand,*
b. *The energy delivered (consumption) and*
c. *The total resulting CO_2 emissions.*

The calculation is determined using the following performance data from modelling the building's specified/designed regulated fixed building services, as sourced from the approved building energy calculation software:

Building floor area (m^2),Notional building energy demand (MJ/m^2), Actual building energy demand (MJ/m^2), Notional building energy consumption (kWh/m^2), Actual building energy consumption (kWh/m^2), Target Emission Rate ($kgCO_2/m^2$), Building Emission Rate ($kgCO_2/m^2$

Example Calculations
Step 1

- *Calculate energy demand*
- *Calculate energy consumption*
- *Calculate co2 emissions*

The above figures have to be obtained directly from professional energy analyses software

Step 2: Multiply each parameter of performance rating by its weighting to obtain EPR_{NC} for each parameter:

Performance indicator	*Weighting*
Energy demand:	*0.28*
Energy consumption:	*0.34*
CO_2 emissions:	*0.38*

*Energy demand = energy demand *0.28*
*Energy consumption=energy consumption *0.34*
*CO2 emissions= CO2 emissions *0.38*

Step 3: Awarding the BREEAM credits:
*Total EPR_{NC} = (energy demand *0.28) + (energy consumption *0.34) + (CO2 emissions *0.38)*
Step 4: Compare results with Benchmark scale

BREEAM Credits	*EPR*	*Minimum Requirements*
1	*0.05*	*Requires a performance improvement progressively better than the Target Emission Rate (TER) required for Building Regulations approval.*
2	*0.15*	
3	*0.25*	
4	*0.35*	
5	*0.45*	
6	*0.55*	*BREEAM Excellent level (≥6 credits): Requires a CO_2 parameter for the EPR_{NC} calculation of 0.22. This is equivalent to a 25% improvement on the TER.*
7	*0.59*	
8	*0.63*	
9	*0.67*	
10	*0.72*	
11	*0.75*	*BREEAM Outstanding level (≥10 credits): Requires a CO_2 parameter for the EPR_{NC} calculation of 0.30. This is equivalent to a 40% improvement on the TER.*
12	*1.79*	
13	*1.83*	
14	*1.87*	
15	*1.90*	*Requires a CO_2 parameter for the EPR_{NC} calculation of 0.38. This is equivalent to a 100% improvement on the TER i.e. zero net CO_2 emissions.*

Figure 5-7 Process of Ene1 evaluation in BREEAM

Similarly, water efficiency can be assessed according to BIM data, using building simulation tools. The tools then can facilitate BREEAM assessment by providing predicted water consumption quantities for water consuming systems such as urinals, WCs, baths showers, taps, washing machines and dishwashers. BREEAM credits can also be awarded when '*Water-efficient equipment'* is installed and '*Water leak detection and prevention devices*' are attached to any water-consuming equipment; the BIM model can provide these data attached to individual equipment. Figure 5-8 shows an example of one of the Wat BREEAM criteria(Wat 02).

Wat02: Water monitoring: one credit can be awarded where a water meter is specified for each building or tenanted space in a development and for any areas or plant within a building

Figure 5-8 Process of Wat 02 evaluation in BREEAM

Some of the Transport (Tra) issues (Tra01 Public transport accessibility andTra02 Proximity to amenities) can be directly assessed in the BIM model; this can be done by exporting a local map to the modelling environment. The majority of BIM tools possess these features, hence, by using GBS features to define the location, distances to the facilities specified by BREEAM requirements, such as transportation, shopping or post office, can be calculated directly. From this, the achieved BREEAM rating can be significantly affected once the building is transferred to a different location.

An analysis has been conducted to specify the requirements of BREEAM, and to quantify the source of data that is needed for the performance assessment process. The analysis results are given in Figure 5-9; it shows that more than 50% of compliance requirements need to be addressed by the user; this is due to the fact that the current version of the BIM model lacks a representation of certain domains of data. However, it should be noted that much of this data is related to checks on supporting documentation, i.e. contracts, user guides and other documentation.

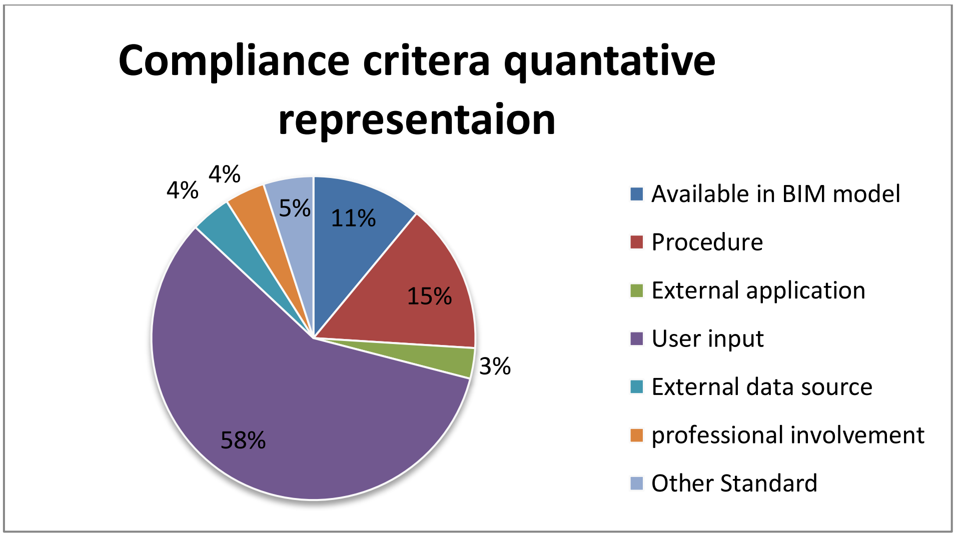

Figure 5-9 Analysis for all the data needed for the BREEAM assessment process

Even though the majority of data for the compliance analysis comes from the user, many data items can be sourced from external sources. A total of 15% of the assessment criteria can be obtained by implementing short procedures, which calculate a piece of data based on other data items within the BIM model. Table 5-1 gives a few examples of these procedures, based on the evaluation of the BREEAM-HEA (Health and well-being).

Table 5-1 Procedures examples HEA-BREEAM issue

Topic	Property	IFC Type	Issues Appearing In	Defination
Space	plan depth	double	HEA02	Plan Depth=Max(width of the floor, length of the floor)
Space	room depth	double	HEA01	room Depth=Max(width of the room, length of the room)
Space	percentage of window wall as seen from inside	double	HEA01	Wall area= If(rectangle, width of the wall (from inside) * height of the wall (from inside), sum(area of all rectangles)) Total Wall Area=sum(Wall area) Window area = If(rectangle, width of the Window(from inside) * height of the Window(from inside) , sum(area of all rectangles)) Totall Window area= sum (Window area) percentage of window wall as seen from inside= Totall Window area / Total Wall Area
Space	floor area	double	HEA05	Floor area= If(rectangle, width of the floor * length of the floor, sum(area of all rectangles))
Space	room volume	double	HEA05	Room area= If(rectangle, width of the room * length of the room, sum(area of all rectangles)) Room Volume=Room Area * Room Height

It can be concluded that there are a diverse range of aspects covered by building codes and regulations. This diversity presents compliance requirement using different expressions, according to the requirement modality. The traditional textual presentation of compliance requirements needs to be transformed into a more logical expression, while preserving the same context to deliver their requirements. Although there are enormous barriers to achieve such a conversion, it is central to the development of smart compliance measure procedures to assess the regulatory compliance of building design.

5.2 Transformations of regulations into rules

Performance-based regulations are complicated in their nature (Bazjanac, 2004). As previously discussed, different types of criteria need to be dealt with in various ways, in order to achieve different levels of automation. The transformation of regulations into rules starts with understanding the information structure within the textual statements. In essence, the conversion consists of two significant steps:

1. Extracting the logical structure of the rules.
2. Extracting the data requirements from the text of the rules.

The first step comprises identifying the compliance requirements from the original standard document. Each requirement is then recapped as a single rule. A statement within a regulation may consist of multiple rules; this step requires experts with experience in the domain of assessment and the terms of the regulations they are processing. The aim of step two is to identify the data elements within each requirement. Consequently, this enables the conversion of rules into computer-understandable logical statements.

5.3 Decision Logic

To facilitate breaking down the complicated regulatory statements in order to convert them into machine-readable rules, the targeted regulatory data has been re-organised using a conditional logical decision tree.

Within a regulatory statement, compliance criteria may comprise multiple check decisions. Each of these decisions can either:

- Acquire BREEAM credit if the decision has been met
- The decision is contingent with supplementary decision(s), all conjugated with 'And'. When the series of And-Decisions has been met, BREEAM credit(s) are obtained
- Multiple decisions are separated with the disjunction 'Or', hence, either decision has been met will lead to BREEAM credit.

A decision tree has been generated for every regulatory statement to represent the logical structure of compliance criteria. The technical aspects of the decision tree have been expanded using the logical spreadsheet (Ragsdale, 2010), as illustrated in Figure 5-10, which shows the detailed actual data of the compliance criteria of a BREEAM issue (EnE-5), represented using a standard spreadsheet feature. Each cell of the spreadsheet represents a 'check box', which contains a single decision used for evaluating whether a building is in compliance or not.

The format of this spreadsheet was developed to ensure that it was powerful enough to represent all of the requirements within the target regulation. The concept of decision tables is not sophisticated, but it has proven to be useful and effective (Albright et al., 2009).

Figure 5-10 Decision spreadsheet of BREEAM issue (Ene5 01)

In the above examples, each box contains at least one decision to be made, or a requirement, a definition, or a subsidiary box. Usually, the boxes correspond with the document, chapters, sections and clauses of the regulation. Each check represents a set of decisions within the same scope, and it will eventually produce a single decision, either true, false or unknown, which refers to another decision. All decisions made within a requirement box can be made without knowledge of decisions made in other requirements boxes (except those within it). Every rule condition presented in a single cell has two potential results (yes or no). The values in the cells are quite simple; each cell contains a description of a single requirement. When the requirement is checked, there are several potential outcomes:

- Credits are awarded according to the check results.
- The check failed and no credits are awarded.
- The check continues to the next cell of the spreadsheet.
- Another requirement elsewhere within the spreadsheet needs to be checked. That includes the embedded tables of requirements. This is done by using the ‘go to’ command to refer to the next criteria.
- Criteria are not applicable to that particular case.

These Check boxes are used to contain the actual tagged text. A check is the fundamental element within the mark-up scheme that the current system is using.

5.3.1 Converting normative documents into explicit rules

5.3.1.1 RASE

RASE is a methodology for adding logical information and meta-data to a textual document, to convert the textual descriptive statements of standards and regulations into explicit rules. It has seen previous use in the area of automated compliance checking (Hjelseth and Nisbet, 2011).

Theoretically, RASE views each regulatory decision as having a series of sub-tests that must be satisfied. RASE describes each decision by breaking it down into "requirements" associated with the future imperatives 'must' or 'shall'. These checks are only applicable in certain pre-defined conditions, and are applied to certain objects i.e., windows, doors, walls etc. These requirements (R) are the first of four RASE operators that are utilised in Figure 5.11. In order to examine whether the decision is satisfied, it must first be determined which objects are in scope. This is done using three more RASE operators - (Applicabilities (A), Selection (S) and Exceptions (E)) - to mark up each decision phrase within the regulations.

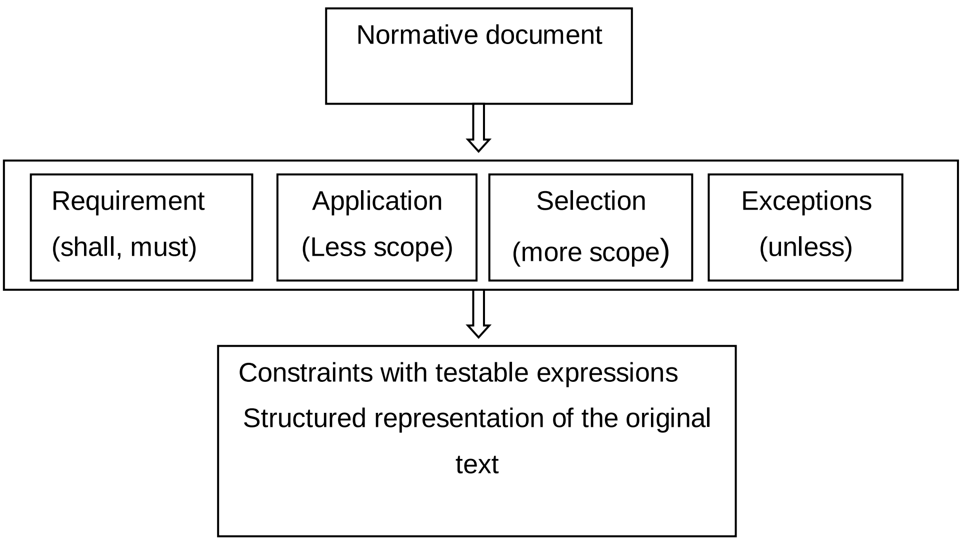

Figure 5-11 RASE logical structure

The RASE methodology has been adopted for several categories of documents: 1) Standard document with implementation per case NS 11001-1.E:2009 Universal design of building constructions - Part 1: Work buildings and buildings open to the public; 2) Standards with tables, that have been implemented in the Dubai regulations; 3) Guidelines document which has been applied (case - GSA court design guidance document, USA). In each case, the regulatory clauses and phrases have been converted into logical statements ready for automated compliance checking. (Hjelseth and Nisbet, 2011). This implementation demonstrates significant advantages, in terms of clarity of conceptual intention of the generated statements, and ease of adoption.

5.3.1.2 Statements Mark-up using RASE

By re-describing the regulatory statements using the logical decision spreadsheet, each individual decision statement has been placed in a cell within the decision spreadsheet. However, regulatory statements are written in technical/legal language for processing by professionals with experience in the domain, and have not been structured for computer processing (Eastman et al., 2009b). To separate the compliance requirements and their applicability, the regulations need to be further re-ordered into an applicable logical structure. This is done by adding additional meta-data to the regulation using RASE, in a process called “Marking Up”. This process of marking up allows the addition of extra semantic information to the regulation. To facilitate utilising RASE adoption, AEC 3 LTD. has developed a graphical tool to apply to the RASE operators.

By utilising RASE, the assessment criteria have been re-written in Requirement 1, simply by copying and pasting the plain text from the original document, however some texts have been re-formatted to facilitate extraction of the information. Every single decision from compliance requirements within the spreadsheet has been marked-up. The mark-up process is to identify ‘objects’ which have ‘properties’ that need to comply with the requirements of the regulations by implementing the previously explained RASE methodology. After the mark-up process has been completed, the required information to be extracted from the BIM model has automatically been summarized.

The idea behind using this software tool is to import the textual statements from the original standard document, and to convert them to Extensible Mark-up Language (XML) format. Basically, this requires 1-tool re-structures of the original sentence with an encoding format, by applying a set of XML syntax. Following the encoding, the four operators of the RASE methodology are added. The XML format is both human-readable and machine-readable, as shown in Figure 5-12; this figure illustrates an example of a text imported into Require1, with the four RASE operators added.

```
<head>
<link rel='stylesheet' type='text/css' href='AEC3_main.css' />
</head>
<body>
 Ene5:Energy Labelled White Goods <br/>
Where the following appliances are <span class="Requirement" object="homes"
property="appliances" comparision="=" target="true" unit=" ">provided and
have an A+ rating under the EU Energy Efficiency Labelling
Scheme</span>:<br/>
"<span class="Application" object="homes" property="Fridges " comparision=" "
target="" unit=" ">Fridges</span> and <span class="Application"
object="homes" property="freezers" comparision=" " target="" unit="
">freezers</span> or <span class="Application" object="homes"
property="fridge-freezers" comparision=" " target="" unit=" ">fridge-
freezers</span>(1 credit)<br/>
Where the following appliances are <span class="Requirement" object="homes"
property="appliances" comparision="=" target="true" unit=" ">provided and
have an A rating under the EU Energy Efficiency Labelling
Scheme</span>:<br/>
"<span class="Application" object="homes" property="Washing machines"
comparision=" " target="" unit=" ">Washing machines</span> and <span
class="Application" object="homes" property="dishwashers" comparision=" "
target="" unit=" ">dishwashers</span> <br/>
AND EITHER<br/>
```

Figure 5-12 XML representation of Mark –up process

An example of the four RASE operators utilised in the methodology of this thesis is shown in Figure 5-13, where each colour represents a single operator.

All framed walls, floors and ceilings not ventilated to allow moisture to escape shall be provided with an approved vapor retarder having a permeance rating of 1 perm (5.7 × 10 –11 kg/Pa × s × m2) or less, when tested in accordance with the dessicant method using Procedure A of ASTM E96

Exceptions

1. **In construction where moisture or its freezing will not damage the materials**
2. **Where other approved means to avoid condensation in unventilated framed wall, floor, roof and ceiling cavities are provided.**

Figure 5-13 RASE Application using Require 1 tool AEC3 Ltd.

- ***Requirement*: Represents the criteria that are required to be true for a specific decision. It allows the specification of the decision to be made. The requirement statements often start with obligation terms, such as *shall*, *must* and so on. A requirement or definition is highlighted in blue, as shown in Figure 5-13.
- ***Application***: Restricts the scope of the decision. The *applies* statement is highlighted in green in Figure 5-13. The check applies to the filtered set of items, which are identified separately as an apply tag, for example, the apply tag may indicate that a decision applies to “external” doors only, or only to “Naturally Ventilated” rooms.
- ***Selection***: The *select* statement is highlighted in purple in the example in Figure 5-13. Each *select* statement serves to expand the scope of the decision. Often, a check contains a list of the selection of items to which it relates. There is a dictionary of phrases to define all of the terms used to describe the alternative items. A key feature is that each select statement increases the number of relevant items that are considered, for example, “walls”, “floors” and “ceilings”.
- ***Exception***: Specifies the cases to which the check does not apply. An exception is highlighted in orange on the previous example, illustrated in Figure 5-13. The *exception* tag also filters the number of items within the scope of the decision.

As RASE operators are added to the text, the following meta-data is also added for each tag: topic, property, comparison, values and units. This is illustrated in Figure 5-14

- **Topic:** The topic is the identification of the “thing” in the building that has a test applied to it, such as a room, window or door.
- **Property:** This identifies some aspect or property which topic is tested against, e.g., a window may have a U-value, or a door may have a material type.
- **Comparison:** This is how a property is assigned a comparative function that is then utilized by the Value operator. Ideally this should be given in the form of a mathematical symbol for example = (equal to), > (greater than) etc., but if not, then appropriate descriptive text can be used.
- **Value:** The Meta data value represents numerical or logical values of what the property should be compared against. In several places, values are taken from other regulations. If it is possible, the value is added directly from the other source. If not, then a clarification to where to obtain the value can be added. This can then be dealt with by a process of iterative refinement. Also, there are some cases where regulations require that something is certified or approved by a registered person; in these cases this should be stated in the value field i.e. “approved by ...”
- **Unit:** This operator represents the unit of measurement that is appropriate for each value i.e. %, metres etc. It is accepted that in many cases there is no unit – in this case the field should be left blank.

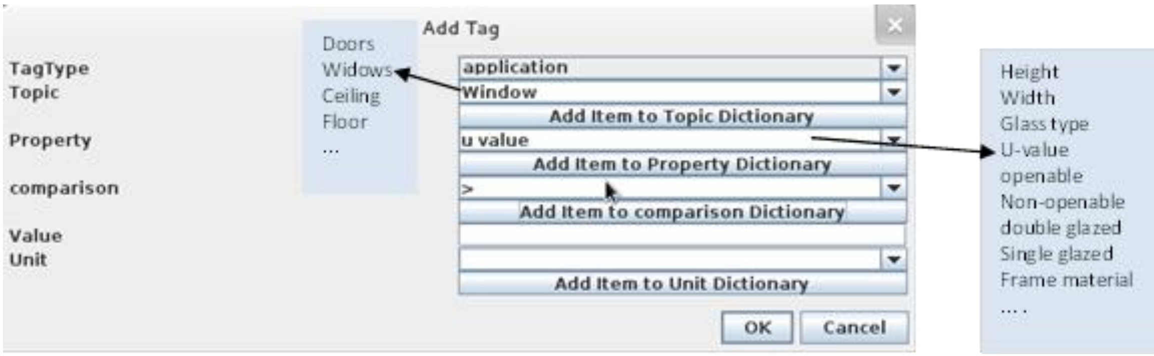

Figure 5-14 Adding Meta data to RASE operators using Require 1 tool AEC3 Ltd.

The majority of the regulatory issues have been extracted directly, where the text formats are clearly and logically understandable. However in some issues the information is nested; in these cases the extraction of rules has been accomplished by reformatting the original text.

Although the RASE methodology explicitly adopts normative expressions to convert the statements into explicit rules, not all of the regulatory statements are suitable for this. Poorly-written normative documents with ill-defined compliance requirements may require extra care when used in RASE applications. When the mark-up process is exposed to un-structured 'blurry' text, the text needs to be re-formulated according to its intention before continuing the mark-up. This needs to be done with extra care because the mark-up results will be based on newly-drafted text. This ambiguity needs to be addressed by experts in order for the regulation to maintain the original intention of the text.

To do this, BREEAM professionals from BRE global Ltd (Ltd, 2014) have validated the conversion, using a simple test application that asks a series of questions based on the spreadsheet, simulating the process a BREEAM assessor may go through. The resulting report by the BREEAM assessment professionals asserts that the converted rules conform to the original document. An example of the output from test application is shown in Figure 5-15.

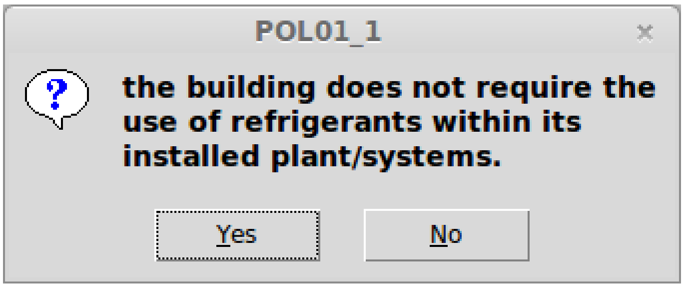

Figure 5-15 Test application for B REEAM criteria

5.4 Rule Generation and Execution

An open-source rule engine has been utilized to execute the requirements for sustainability compliance checking. A rule engine is a software system that executes complex decision logic. The main motivation for utilizing a rule engine is that it separates the rules and programs that process the rules efficiently (Adamczyk et al., 2008, Thomas H Beach, 2013b). For the implementation described in this thesis, the DROOLS rule engine was selected (Drools, 2013).

In order for the DROOLS rule engine to process the decision spreadsheets and the RASE meta-data that has been added to the individual cells within the spreadsheets, the spreadsheets and meta-data must be converted into a format understandable by the rule engine, namely DRL (DROOLS Rule Language) (Community, 2013). This conversion is done by using a rule compiler, which converts textual rules into DRL by utilizing a series of logical formulas, based on the decision spreadsheets and the RASE tags within the cells within the spreadsheets. The generated DRL is then processed by DROOLS into an executable code.

Each cell in the decision spreadsheet is treated as a single rule. Rule execution is done in two steps: firstly, to determine if the rule is in scope, and secondly if the rule has been passed or failed. The logical formula shown in Figure 5-16 is used to process the rules. In this figure, S1 and S2 represent the previously-explained "*Select*" RASE Tags - E1,E2 represent "*Exception*" tags and A1 and A2 represent the "*Applies*" tags. This means that, in order for a rule to be applicable, at least one selection must be met, all of the applicability criteria must be met, and all of the exceptions must not be met. Once a rule has been determined to be in scope, it must then be determined whether it has passed/failed. This is done when the two pre-defined requirements “R1” and “R2” are met.

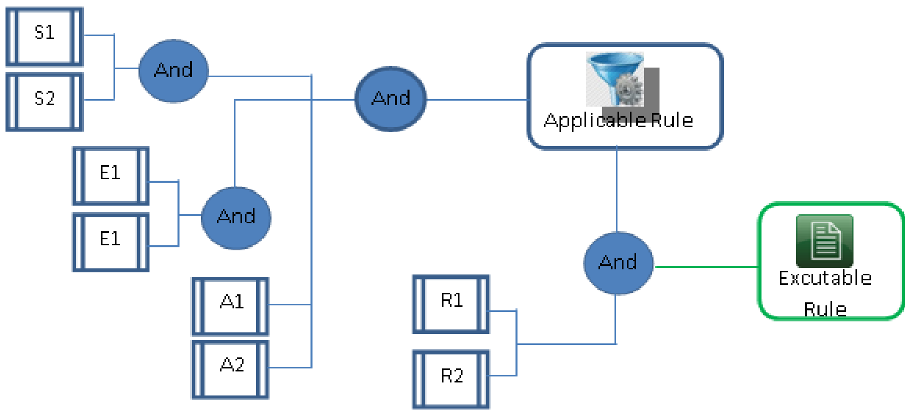

Figure 5-16 Scope of logical formula of rule processing

Using these formulas, the rule compiler converts the tagged documents into DRL rules. Figure 5.18 show an example clause extracted from a BREEAM assessment document. This clause verifies whether the principal contractor has a suitable score from the compliant construction scheme (CCS), and awards 1 credit if successful. This particular clause has one application: that the rule only applies to contractors who are the “principal contractor”, and two requirements - that the CCS score is greater than 24 and that it is less than 31.5. The details of DRL produced by running this clause through the rule compiler are shown in Figure 5-17

Where the principle contractor achieves compliance with the criteria of a compliant scheme, ccs score between 24 and 31.5

```
rule BREEAM_MAN2_1-1SF salience 100
when
not exists Contractor(type==’principal’)
then
result.isNA(’BREEAM_MAN_2_1-1’)
result.pass(’BREEAM_MAN_2_1-1’)
end
rule BREEAM_MAN2_1-1ST salience 100
when
not exists Contractor(type==’principal’)
then
result.total(’BREEAM_MAN_2_1’,1)
end
rule BREEAM_MAN_2_1-1F
when
not exists Result(id=’BREEAM_MAN2_1-1’,na==true)
exists Contractor(type==’principal’, ccs_score <24, ccs_score > 31.5)
then
results.fail(’BREEAM_MAN2_1-1’)
end rule BREEAM_MAN_2_1-1T
when
not exists Result(id=’BREEAM_MAN2_1-1’,na==true)
forall ($contractor: Contractor(type==’principal’)
Contractor(this=$contractor, ccs_score >=24, ccs_score <=31.5)
)
then
results.pass(’BREEAM_MAN2_1-1’)
results.award(’BREEAM_MAN2_1’,1)
end
```

Figure 5-17 Rule complier application to BREEAM criteria

The code block shows that four DRL rules are generated for this clause. The first checks if the clause is N/A, the second checks if the clause is applicable, the third checks if it fails, and a final rule checks if it passes. The rule complier has been utilized to convert all compliance criteria into rules. Then, the rule engine executes the rules to check compliance and report the results accordingly.

Using the DROOLS software, the rules were executed by the rule engine. To evaluate the efficiency of the results, the output from the rule engine was compared with the output of previously-validated spreadsheets. There were several technical issues and errors which were captured at this stage of validation, however the output from the rule engine was consistent with the output from the spreadsheet. These results were expected because the rules were originally generated according to the spreadsheet data for the first place. Figure 5-18 shows an example of a generated rule.

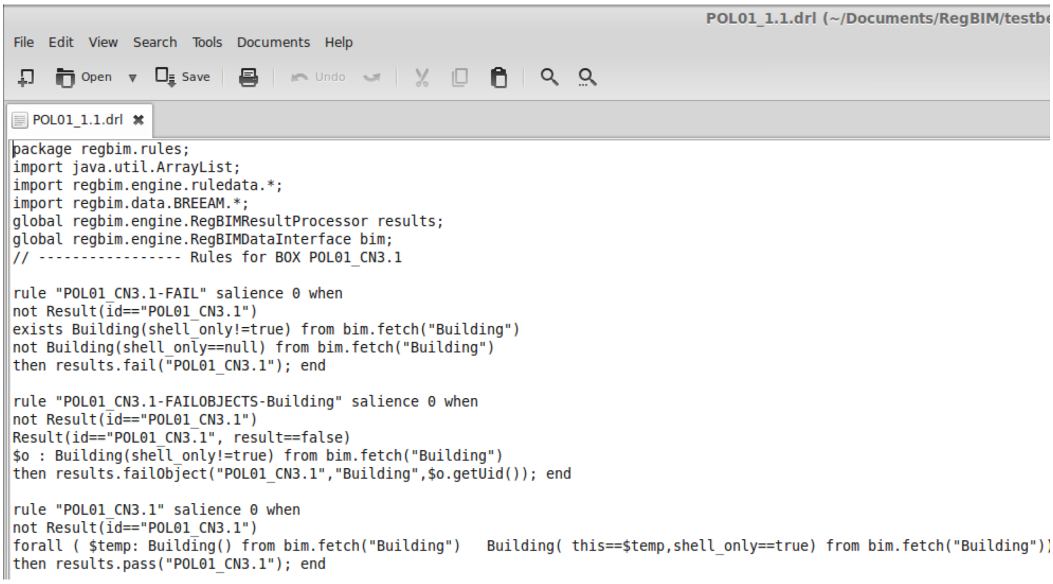

Figure 5-18 Rules generations from decision logic spreadsheet

5.5 Conclusion

This chapter has described the methodology for the conversion of sustainability regulations embedded within traditional documents, into computer executable rules that can be executed by a rule engine. This methodology can be applied in other domains of regulation with contents similar to that of BREEAM. However, the difficulty of the rules generation depends on the complexity of the original regulatory statements in describing the context. The use of RASE has been determined to be reliable in handling different categories of texts. The use of mark-up to add meta-data to the tagged texts provides a robust foundation for an automated model checking system. This is the key to facilitate mapping of the compliance requirements to a building information model (BIM), and to automate the compliance checking.

The methodology can support semi-automated compliance checking of building design and performance. The system examines the provided sets of data against the pre-defined rules embedded in the compliance checker. This allows the user to achieve comprehensive recognition of what action is needed to achieve better design that complies with the targeted regulation, and what data is needed for compliance checking at every stage of the design process.

The RASE methodology is time-efficient, and capable of capturing compliance requirements in a format that allows direct testing by the compliance checking engine. Moreover, the accuracy of the extracted rules has been checked by comparing the original standards to the decision logical spreadsheet, and to meta-data that has been extracted using the RASE methodology.

Chapter 6

BIM Conformed Regulatory Data And Compliance Check

This chapter will address the inter-operability issue; the following sub-sections will describe different approaches to bridge the gap between compliance requirements and the IFC data model. This includes direct mapping (Section 6.3.1), and in-direct mapping where new property sets are identified as extensions to the current IFC (Section 6.3. 2).

6.1 Introduction

The rules-based sustainability compliance checking system introduced in Chapter 5 has transformed sustainability compliance checking into a semi - automated process. The system stores compliance requirements in a digital format, and enables users to examine their designs against these requirements by providing the relevant information. In this chapter an examination is presented of the potential for integrating the system with building information models, in order to achieve direct extraction of compliance requirements from them.

To facilitate data exchange for the purpose of compliance checking within the construction industry, most of the compliance checking developments utilise Industry Foundation Classes (IFC) entities, identified by BuildingSMART International Ltd - access to this data is available at (buildingSMART, 2013a).

The IFC data model is comprehensive in terms of the building design data that it incorporates. However, existing compliance checking solutions extract only architectural and structural design data from a given IFC model. As a result, existing checking solutions focus on checking compliance through the use of simple rules concerning geometric and spatial attributes, such as access dimensions, door sizes, or wall thickness.

In order to check building design compliance with environmental sustainability standards, all of the data requirements for the compliance checking need to be summarised; in addition, the presence of compatible data items within the contexts of IFC data model needs to be investigated. In other words, the inter-operability between sustainability compliance checking systems and the BIM environment must be ascertained.

6.2 Dictionary Based Translation to a Domain Compliant IFC Model

As part of transformations of textual regulations into digitally-formatted explicit rules, using the spreadsheet and the decision logic approach and RASE mark-up, all compliance criteria were critically analysed. A description of all the terms used within the targeted regulation (BREEAM) has been produced, in the form of objects, properties and requirements - an example is shown in Figure 6.1, and an entire list has been summarised in Appendix (A). This accumulation of data automatically generates a dictionary for all of the data items that the rules engine processes when it runs the compliance checking. The dictionary is an XML file that acts as the rules engine container, and stores the data items, decision functions and rule sets for applications. All of the elements of the data model referenced by the rules must be available in the dictionary, therefore there is no limitation to the number of rules sets and the amount of data stored. In addition, the dictionary allows the adding additional data, whenever an update to the regulation occurs and new rules are set; this means that once the original dictionary has been generated, it can always be updated with new data items and rule sets.

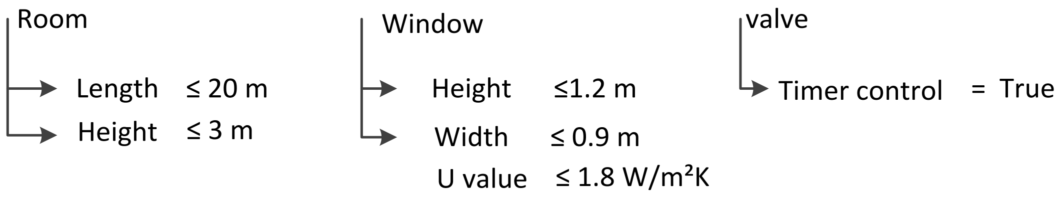

Figure 6-1 Examples of dictionary taxonomy

6.3 Mapping the dictionary data to IFC

By exploring the IFC data model, it has been realised that all of the main building objects to be tested for compliance are included in the IFC data model. However, the pre-defined properties attached to these objects do not necessary fulfil the requirements for compliance checking; there are a plethora of characteristics and descriptive attributes that need to be added to the IFC data model, in order to establish a domain-compliant IFC ready for the automated compliance check. To this end, different types of mapping have been employed as described in the following sections.

6.3.1 Direct mapping to IFC

When the information is explicitly demonstrated in the IFC data model, and is compliant with the definitions that are described in the dictionary, a direct mapping between the dictionary terms and the IFC can be implemented.- this is illustrated in Figure 6-2. In this figure, the object *'Building'* has pre-defined property sets that fulfil some BREEAM compliance requirements; property sets are a mechanism by which the user can attach object-specific data to building elements (Plume and Mitchell, 2007). The object '*Building'* and its three properties *UsedForFlammableStorage*, *ResidentialRetailIndustrialPrison* and *DaysReserveWater,* are extracted from the meta-data that are added to the BREEAM regulations. These are mapped using the dictionary onto their counterparts in the IFC model, and *'Building'* is then mapped onto *IFCBuilding*; *UsedForFlammableStorage* is mapped onto a *FlammableStorage* data item within the *PSET_SpaceFireSafetyRequirements,* which is a property-set of an *IFCBuilding*; *residential, retail, industrial, prison* is mapped onto *Occupancy Type* within the *P_SETBuildingCommon*.

Although the existence of property sets matched to compliance requirements streamlines the automated extraction of data, there are numerous requirements that do not exist within the current IFC specification. In such cases, the required data item will be added to the IFC specification as an extension. Table 6-1 summarises the data items adopted by the BREEAM regulations, and the comparable entities in the IFC context

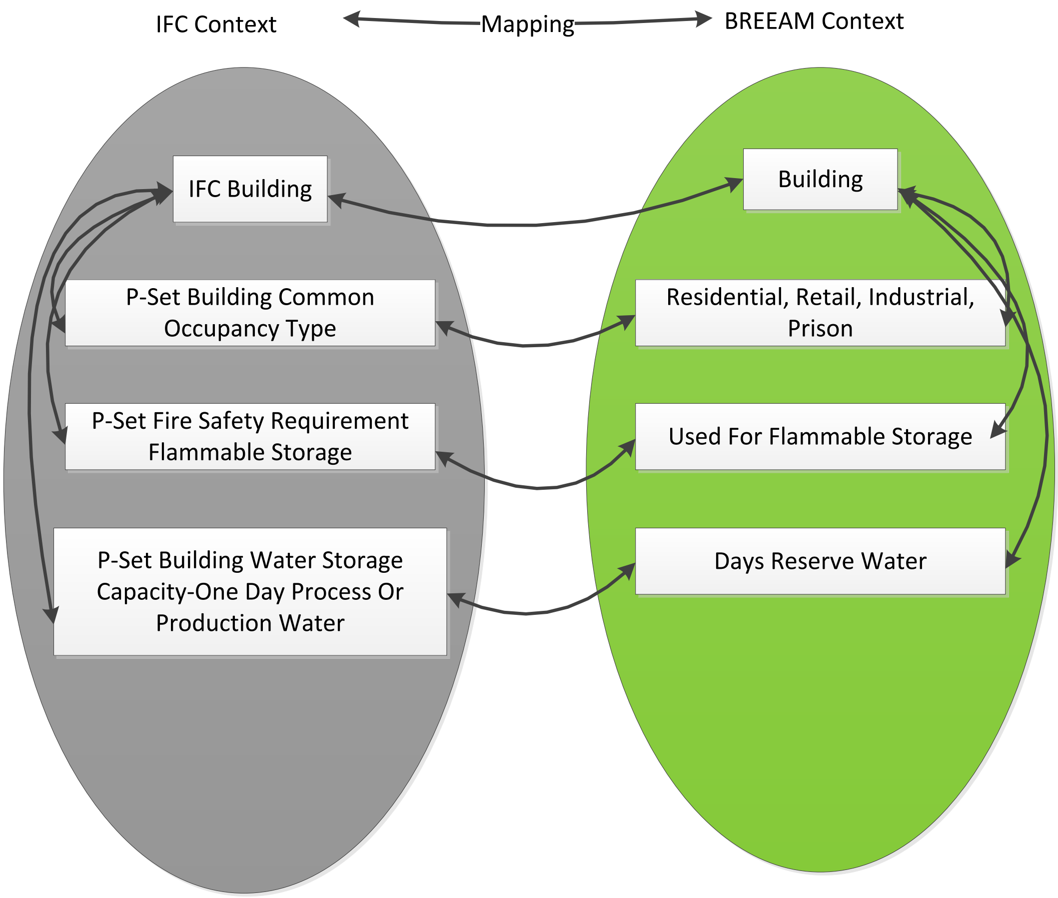

Figure 6-2 Describes Extracting the type of building from IFC schema is done directly

Figure 6-3 shows the Express-G diagram of the properties of the *'IfcBuilding'* entity. The direct mapping of *'Building'* elements is essential at the early stages of compliance checking, in order to identify the building type and to direct the process to the relevant regulatory schema. For example, in BREEAM assessment, when the building type is a healthcare or hospital building, the weighting of '*Health and wellbeing*' issue credits exceeds those concerning energy use, due to the functional requirements of the building. Although the use of low/zero carbon technologies is still recommended, achieving an outstanding energy performance is quite difficult in healthcare buildings, due to the necessity to operate energy-intensive systems such as air-conditioning and heating.

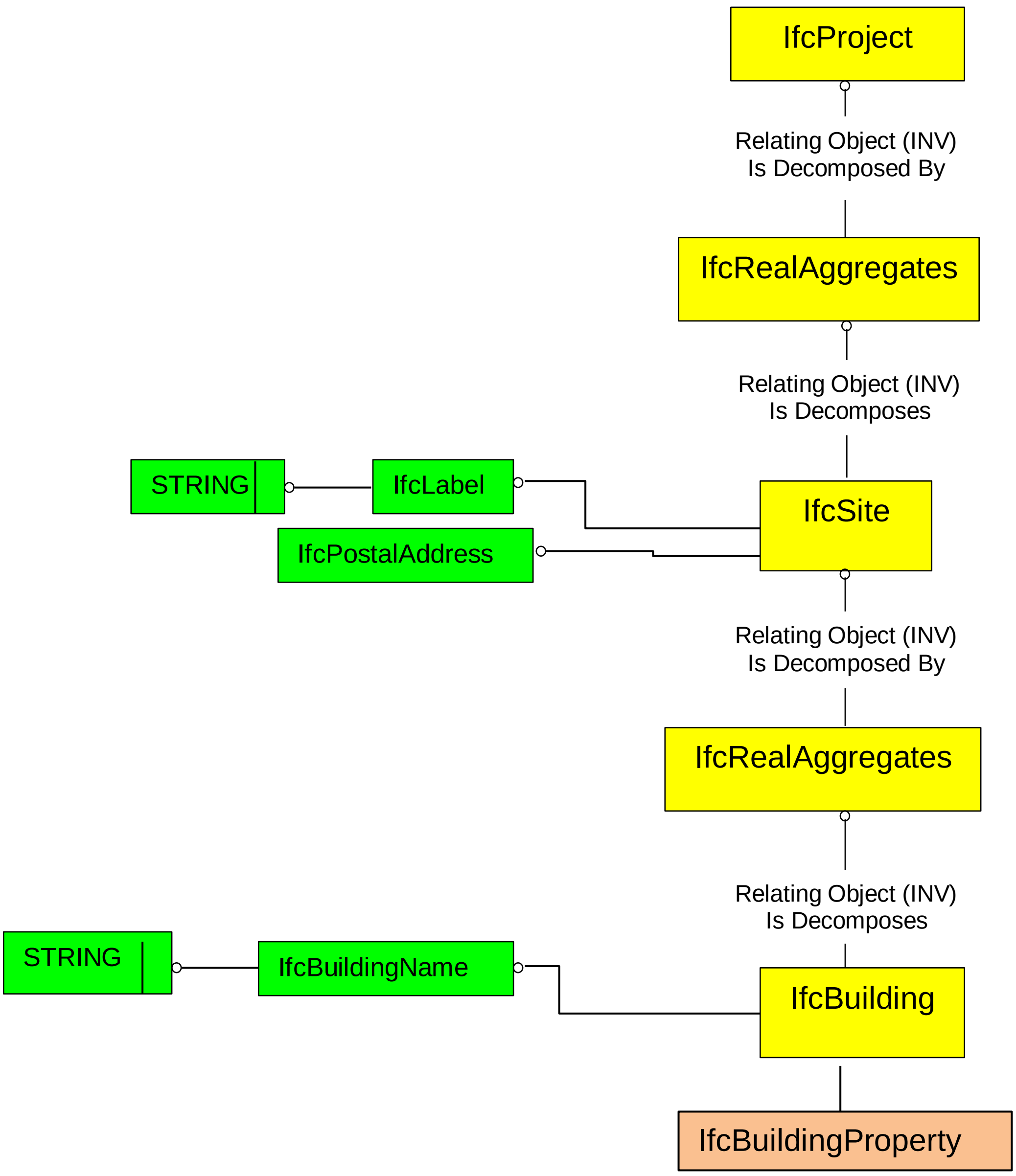

Figure 6-3 Express-G diagram of the properties of 'IfcBuilding' entity

When the compliance requirement takes the form of *'existing objects'*, the *'distribution system'*, *'building type'*, *'site location'* and *'geometric data of building elements'* can be extracted directly from the IFC data model generated by the BIM-authoring tools. All other input data relies either on external data repositories, external applications, or needs to be added manually by the user.

Table 6-1 BREEAM list of data entities in IFC context

BREEAM list of data entities in IFC context			
Building	Development Site	Moving Walk	Window
Dwelling	Dwelling	Noise Impact Assessment	Building
External Lighting	Ecology Report	Operational Waste Facility	Composting Space
Project	Environmental Management System	Plant	Irrigation System
Storage and Delivery Areas	Escalator	Post Occupancy Evaluation	Kitchen
Access Statement	External Lighting	Prison Cell	Laboratory Area
Aftercare Commitment	Facilities Management Contract	Project	Plant
Appliance	Fume Cupboard	Rainwater System	Refrigerant System
Boiler System	Grey water System	Recyclable Waste Storage Area	Space
Building	Illuminated Advertisements	Recycling Containers	Surface Water Drainage System
Building Travel Plan	Irrigation System	Recycling Policy	Vehicle Wash System
Building User Guide	Kitchen	Refrigerant System	Water Meter
Composting Space	Laboratory Area	Site Waste Management Plan	Water Supply
Contamination Site Investigation	Lifecycle Cost Analysis	Space	WC Area
Contractor	Lift System	Storage and Delivery Areas	Window
Design Consultation	Low Zero Carbon Feasibility Study	Swimming Pool	

Figures 6-5 and 6-6 demonstrate a mapping example between regulatory terms and IFC. The solid arrows represent mappings within the contexts between the IFC, and the BREEAM terminology used in the regulations.

The object '*refrigerant system*' has been defined in the IFC within *IFCDistributionSystem*. However, the data required does not exist within a standard IFC model. Therefore, a new property set, *BREEAM_RefrigerantSystem_UK,* has been added, and this property set includes the entire data requirement for the refrigerant system object. The name of the property is equivalent to the requirement description within the regulation.

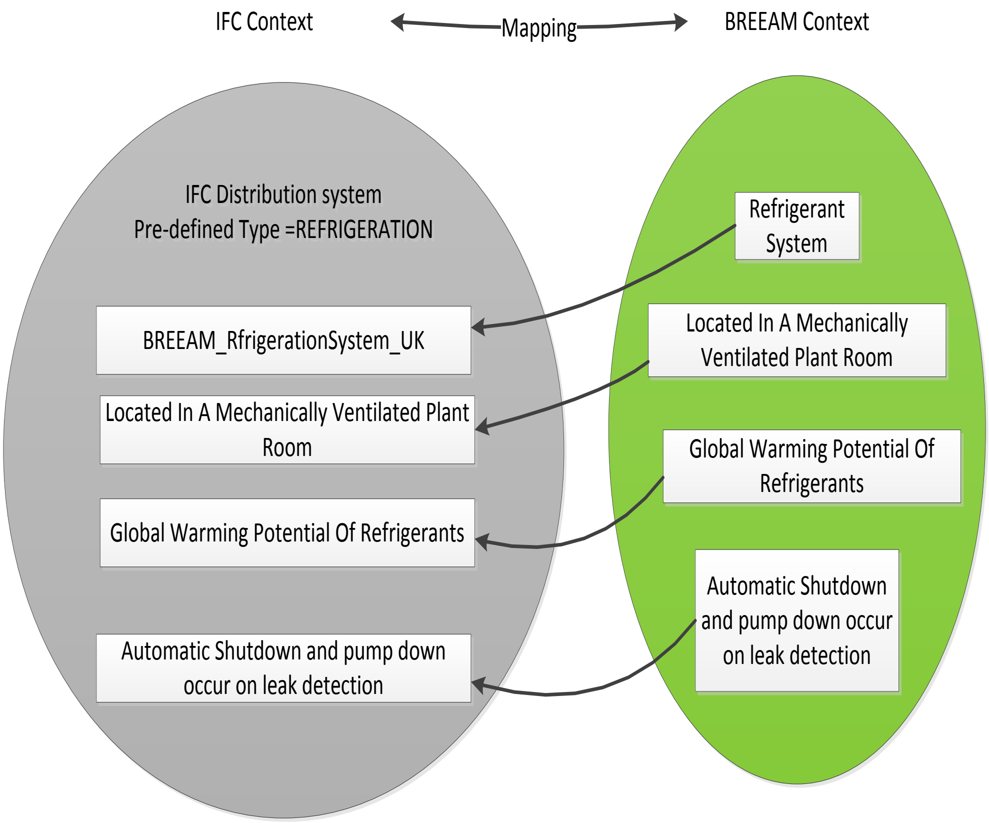

Figure 6-4 Mapping between IFC P-Sets and BREEAM contexts

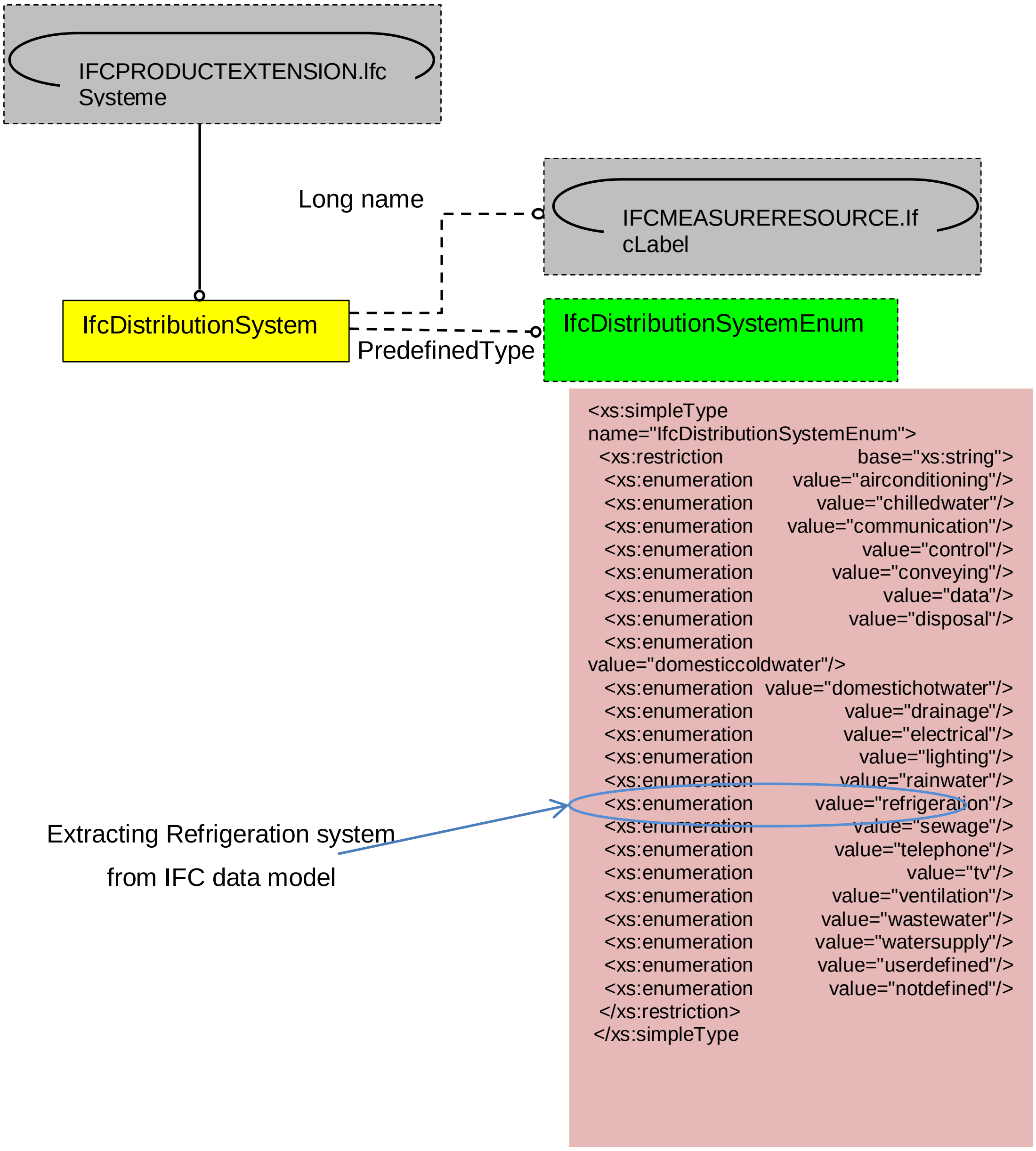

Figure 6-5 Mapping between IFC P-Sets and BREEAM contexts

Table 6-2 lists the data items adopted by the compliance checking system, as defined according to the context of IFC entities.

Context	Concept	Sub-Concept		Value	Type	Raw Type	Occurs
BREEAM	Refrigerant System						POL01
IFC4	IFCDistribution System						
IFC4	PredefinedType		=	REFRIGERATION	IfcDistribution SystemEnum		
IFC2x3	IfcSystem						
IFC2x3	ObjectType		=	REFRIGERATION	IfcLabel		
BREEAM	Refrigerant System	located in a mechanically ventilated plant room			IFCBoolean	boolean	POL01
PROCEDURE	BREEAM_RefrigerantSystem_UK	LocatedInAMechanicallyVentilatedPlantRoom					
BREEAM	Refrigerant System	automatic shutdown and pumpdown occurs on detection of leak or charge loss			IFCBoolean	boolean	POL01
IFC	BREEAM_RefrigerantSystem_UK	AutomaticShutdownAndPumpdownOnLeakDetection					
BREEAM	Refrigerant System	design team confirms complies with institute of refrigeration co2 code of practice			IFCBoolean	boolean	POL01
IFC	BREEAM_RefrigerantSystem_UK	DesignTeamConfirmsCompliesWithInstituteOfRefrigerationCO2CodeOfPractice					
BREEAM	Refrigerant System	leakage charge loss detection system specified which is not based on principle of measuring concentration of refrigerant in air			IFCBoolean	boolean	POL01
IFC	BREEAM_RefrigerantSystem_UK	LeakageChargeLossDetectionSystemSpecifiedWhichIsNotBasedOnPrincipleOfMeasuringConcentrationOfRefrigerantInAir					
BREEAM	Refrigerant System	design team confirm complies with institute of refrigeration ammonia code of practice			IFCBoolean	boolean	POL01

6.3.2 Indirect mapping to IFC

In some cases, compliance checking requirements cannot be mapped directly onto the IFC, but the IFC may contain related data. In such cases, the required data can be obtained by applying a procedure to calculate the required data item. For example, the area of a space can be calculated by the multiplication of the length and width of the space. Another example is the checking of the height of ground level above flood level; this check requires two pieces of information - flood level height and ground level height. To check the compliance for this particular example, flood level height needs to be added from an exisiting database, while ground level height can be obtaind directly from IFC. Figure 6-6 shows the elevation entities in the IFC file (buildingSMART, 2013a).

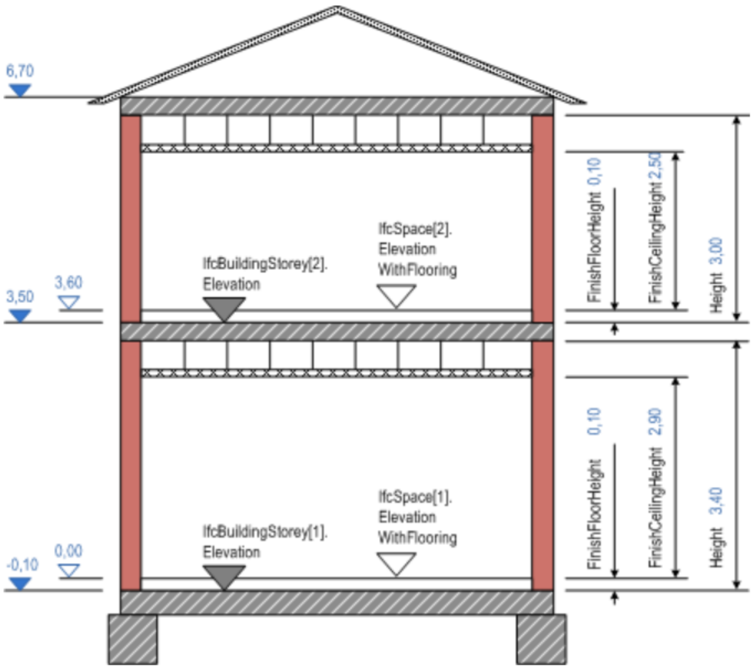

Figure 6-6 Elevation entities in IFC

Some of these procedures are simple mathematical functions, but some are more complex queries of the building model - e.g., determining if a space is insulated - and some act as interfaces to external applications. An example of such an application is the materials calculator; when a list of all materials in a building is given, the calculator fetches the rating of each material from a database, and then performs a calculation to rate its environmental performance. This calculator is a spreadsheet that considers both the material's impact, and the impact of an element in relation to other elements assessed within the building. The results of the *Mat* calculator are based on submitted information, and on the green guide specification. Other assessment processes need some results from analysis applications such as energy simulations. Equally, the assessment of water, NOx emissions, *etc.* cannot be undertaken without supplementary results from analysis applications. The optimum efficiency occurs when these external applications are embedded within the automated checking environment. (6-7) shows a screenshot of an application created by the author to convert the assessment procedure of energy performance into computer code with a user interface. This calculator has been initiated to assess the ENE1 (energy one) issue of BREEAM, however, in order for this preliminary application to run automatically, it needs to be integrated with energy analysis tools, and thus to fetch results for energy consumption, energy demand and CO2 emissions based on 3-D modelling - the manual calculation process is explained in Section 4.3.1.

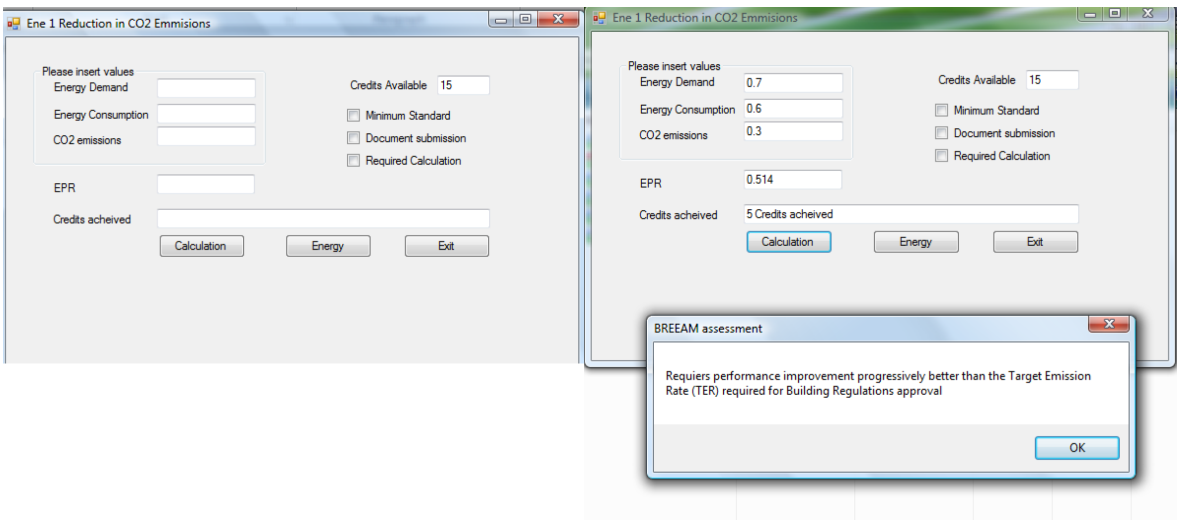

Figure 6-7 BREEAM Calculator

The aim of integrating external into the automated compliance checking process is to extend the capability of the applications; by applying simple computer programming, the application can identify the data requirement, starting with the original design model. The analysis applications may require the input of generic data, some of which can be obtained from the original building model. For example, objects that are involved in the analysis, together with their attributes and relations, can be obtained directly from the building model. This information may need to be re-structured to fit the requirements; for example, building objects may be aggregated to generate a zonal model from a wall-and-slab-based building. In addition, some general information can be obtained from external libraries such as location, weather data, flood zones, wind, rain, *etc.* For every particular analysis application, there is set of unique analysis properties, such as well-formed zonal models for energy analysis. The majority of BIM tools provide powerful application program interfaces (APIs) and software development kits (SDKs) that allow the developers to gain greater value from their investment in BIM software tools, by tailoring them specifically to the needs of a particular requirement.

A fully-automated process for extracting compliance checking data from IFC is un-attainable, since the assessment requirements cannot be obtained from a particular data source without human interaction; interacting with users is a fundamental phase which must precede the compliance checking process. The goal of user engagement is not to provide an overall, definitive evaluation, but rather to provide more meaningful pieces of information that can be helpful to in order to proceed with running the compliance checking application automatically. When the user needs to input a piece of information, the features of the interface constrain this process, to ensure that the information is consistent terminology that is recognized by the rule engine.

6.4 Conclusion

This chapter has described the methodology for the conversion of sustainability regulations embedded within traditional documents into computer-executable rules that can be executed by a rule engine . The rule engine examines the BIM model to check compliance against the regulation. A considerable amount of BIM data has been directly-exploited for compliance checking, and at the same time, the significant limitations of IFC have also been determined. One of the key features of the current methodology is its ability to collect the compliance information, and to use that information to enrich the existing BIM model, and make it compliant with the regulatory requirements.

As a conclusion from the rules-based compliance checking approach, it can be reported that the rules engine can only capture the explicit data requirement from the IFC file. Although the vast majority of the building objects are represented in the IFC, and detailed attributes are attached to these objects, it is still difficult for the rule engine to deal with the implicit concepts, and to track and evaluate attributes of objects whose instances are themselves classes defined in IFC. This fact has motivated the author to seek alternative reasoning-based methods to extract more compliance requirements from BIM data, by using engineering ontologies. This will enable the gathering of some fragmented pieces of axioms from the IFC, in order to build a domain ontology; the development of such an ontology can further facilitate extracting information from an IFC model.

Chapter 7

Case Studies Testing And Usability

In this chapter, Section 7.1 gives an introduction to the main goal of the chapter, explains the reason behind using two case studies, and summarises the technical validation findings presented alongside the methodology description. Section 7.2 demonstrates the first case study 'The Monument pilot project'; this case study highlights the procedure of automated compliance checking using the developed regulatory compliance checking system based BIM, and reveals the deficiency of the current IFC. In Section 7.3, a more-detailed case study is presented to cover an entire BREEAM assessment of the newly-designed orthopaedic hospital building. The assessment has been conducted using both the traditional manual approach, and the developed tools. A conclusion is summarised in Section 7.4, and the results are discussed in Section 7.5 together with a summary of a comparison between the two approaches.

7.0 Introduction

This chapter introduces two case studies that are used to validate and further- develop the sustainability compliance checking tools. The validation is enhanced by conducting a comparison between the traditional BREEAM assessment process, and the current approach. The objective of conducting case study validations is to present a valid, efficient, accurate and scalable system with a visualized, user-friendly interface to manage the sustainability performance of buildings. As will be shown below, the use of the system contributes to improved construction practice by minimising the time for compliance checking, and by assisting the project team to become more efficient in designing better-performing buildings that comply with standards and regulations. The goal of this chapter is to use two case studies to test the developed BIM-based sustainability compliance checking approach. The chosen case studies were designed using different BIM tools (Bentley and Revit). The first case ‘The Monument pilot project’ was provided by Skanska UK Ltd (Skanska, 2014), while the ‘the orthopaedic hospital design project’ was provided by a group of research students at Cardiff University, and was verified by Arup Ltd. (Arup, 2014). Both case studies were used as real-world examples for the establishment of the proof-of-concept of the developed tool.

At the outset, the aim was to have tandem operation of BIM checking software and the traditional human assessment of compliance for Building Regulations, BREEAM and /or Code for Sustainable Homes (CfSH). The objective was to collate the findings of the comparison of the two methods, highlighting the differences, potential advantages in terms of time, cost, increased confidence and reduced risk. An additional aim was to record the current levels of capability and maturity of the BIM process, to accommodate the developed tool and any challenges to be overcome.

BREEAM assessment has been used for the validation process for the non-residential case studies. It was thought that the process for establishing BREEAM compliance was relatively more straightforward than the Building Regulations, so the whole spectrum of BREEAM could be considered.

Both case studies provide BIM models (in Bentley/Autodesk Revit software), that could be converted to IFC’s data model.

The Monument pilot project was used to implement the developed tool on a real project ‘as it stood’, without having the capability to manipulate and amend the model according to the requirements of the compliance checking tool - this project is currently under construction. The pragmatic IFC was used to examine the current coverage scope and required level of detail for automated compliance checking.

A more detailed validation has been conducted using the Orthopaedic Hospital design, with the Revit software. For this case, the designers and the author interacted during the validation phase, to assist with resolving issues regarding the model, IFC and level of details required. The holistic BREEAM assessment has been conducted both manually and using the developed tool, and results from the two compared.
Prior to the case studies, a technical validation of the developed system was carried out for all activities that occur throughout the entire development lifecycle of a BIM-based compliance checking system.

The technical validation process consists of the following three major tasks:

Task one: Breaking down the textual document of the original standards to generate the rules, using the RASE methodology and/or a logical decision spreadsheet. To do this, the BREEAM conversion has been validated by professionals; a test application has been generated to ask questions for every part of data within the spreadsheet, and BREEAM assessment professionals have determined that the converted rules conform to the original document.

Task two: Using the Rule Engine to execute the rules from the spreadsheet. The output of this procedure was validated by checking the expected output from the spreadsheet, which includes checking the data items and structure of the rules.

Task three: Verifying that the computer software reads the rules using the correct code; this was checked by comparing the output from the software with the output from the spreadsheet (validated by professionals).
This means that the validation has been separated into the following stages:

- Extraction of Decision Logic from Regulation Documents

- Conversion of Decision Logic into Computer Executable Rules
- Final Validation of a Case Study Building

For the initial stages of our validation, a sample BIM model has been used. For the final validation stage, real case study buildings (the Monument Pilot Project and Orthopaedic Hospital) were used.

7.1 Case Study (1)The Monument pilot project

7.1.1 About the project

A BIM model of new development in the city of London has been utilized for this purpose. The model has been provided by Skanska UK Ltd (Skanska, 2014) - the model is shown in Figure 7-1, as visualised by IFC viewer (X BIM).

The building is a nine-floor construction of 85,000 sq. ft. of offices, and 3,000 sq. ft. of ground floor retail accommodation. It is designed to achieve a BREEAM 'excellent' rating, which aims to create a high quality, contemporary development of energy-efficient buildings in the City of London.

The BREEAM assessment for the building has been conducted using the developed tool, to verify the efficiency of system implementation on an actual BIM model. The application of the tool also served to examine the usability of the corresponding IFC for sustainability compliance, and to determine the effectiveness of the automated compliance system.

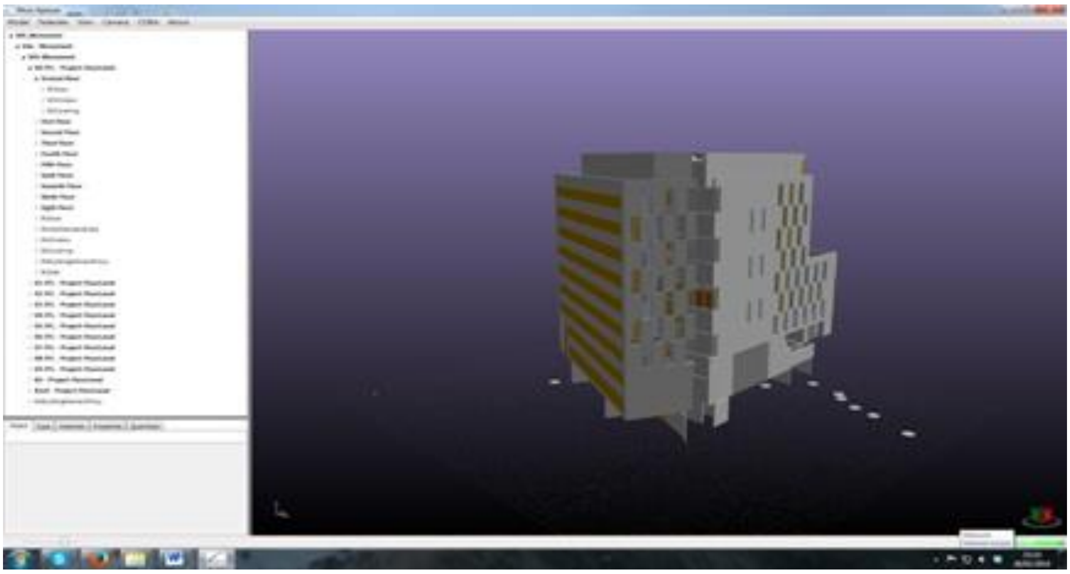

Figure 7-1 The Monument Building using IFC viewer

7.1.2 System Implementation

Although the entire BREEAM output has been verified, this section focuses particularly on BREEAM *Pollution* issue 01 (Impact of refrigerants). Figure 7-2 shows the assessment clause, which is extracted from the original BREEAM textual document (Global, 2011a).

Pol 01 Impact of refrigerants Number of credits : 3

1. **Assessment Criteria**
2. **Three credits**

Where the building does not require the use of refrigerants within its installed plant/systems. OR alternatively, where the building does require the use of refrigerants, the three credits can be awarded as follows:

Two credits

Where the systems using refrigerants have Direct Effect Life Cycle CO_2 equivalent emissions (DELC CO_{2e}) of ≤ 100 $kgCO_{2e}$/kW cooling capacity.

One credit

Where the systems using refrigerants have Direct Effect Life Cycle CO_2 equivalent emissions of (DELC CO_{2e}) of ≤ 1000 $kgCO_{2e}$/kW cooling capacity.

One credit

1. Where systems using refrigerants are contained in a moderately air tight enclosure (or a mechanically ventilated plant room), and an automated permanent refrigerant leak detection system is installed covering high-risk parts of the plant OR where a refrigerant leakage/charge loss detection system is specified, which is not based on the principle of detecting or measuring the concentration of refrigerant in air.
2. The automatic shutdown and pump down of refrigerant occurs on the detection of refrigerant leakage/charge loss.
3. Automatic pump-down to either a separate storage tank or into the heat exchanger is acceptable, but only where automatic isolation valves are fitted to contain the refrigerant once fully pumped down.
4. The alarm threshold that triggers automatic pump down upon detection of refrigerant in the plant room/enclosure is set to a maximum of 2000ppm (0.2%), but lower levels can be set.
5. Use a robust and tested automated permanent refrigerant leak detection system, normally defined as that included on the Enhanced Capital Allowance (ECA) Energy Technology Product List(or an equivalent list).

Figure 7-2 BREEAM- Pol 1 Assessment criteria

7.1.3 Implementation Results

The above clause has been chosen as a representative example of the BREEAM assessment requirements. When the regulatory compliance system is run on the IFC model for the case study building, the rules engine examines the IFC file to capture the data needed for the requirements assessment.

In this particular example, the impact of refrigerants is associated with the presence of the '*Refrigerant system'* within the building model. This object has not been found within the IFC model, and therefore, a warning pane appears to notify the user that the '*Refrigerant system'* object is not found, as illustrated in Figure 7-3.

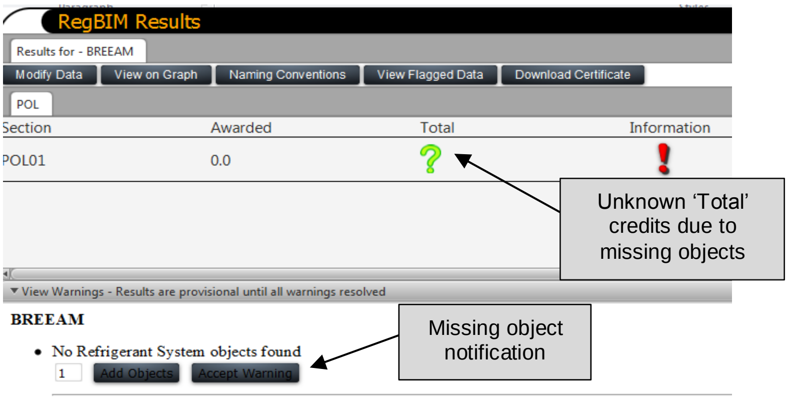

Figure 7-3 System Implementation

The user would then respond to the Rule Engine enquiry and add the missing data. This process is important, as it is necessary to determine whether there is no refrigerant system shown because there is no system in the building, or if there is a refrigerant system but it has not yet been specified (or has not been specified correctly) within the IFC file.

As the missing data are added, the original IFC model will gradually become enriched with the objects that are needed to complete the compliance checking requirements. The rule engine then processes the enriched IFC model to reveal the real-time performance. In addition to the compliance results, the compliance checker gives a detailed description of the minimum amount of data needed to achieve the maximum number of credits for better performance - Figure 7-4 shows the interface of the results visualization.

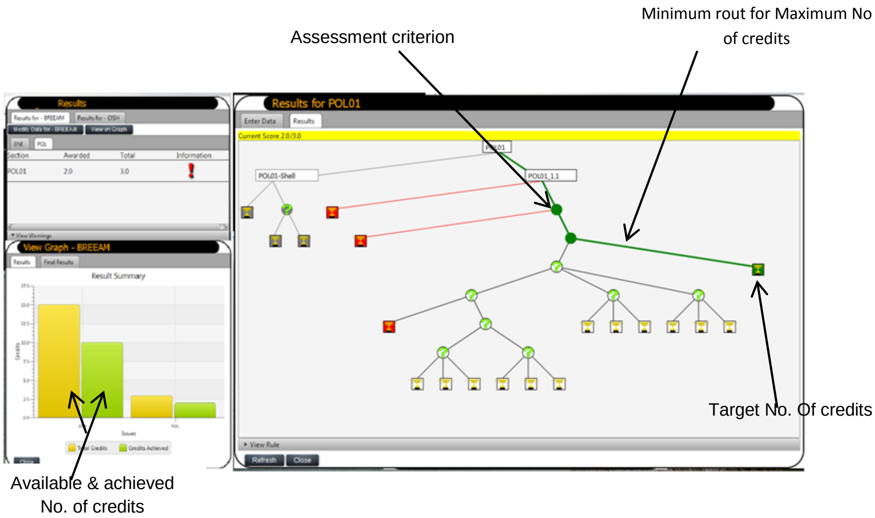

Figure 7-4 Results Visualization

In this example, which is specific to the BREEAM POL01 issue, the assessment results failed to award the *'three credits',* because the building does not comply with the requirement: *'if the building does not require the use of refrigerants within its installed/ plants system, 3 credits are awarded'*. However, the *'one credit'* is awarded according to the compliance requirements achieved (Figures 7-5 & 7-6). The Rule Engine investigates the tree of BREEAM POL01 issue compliance requirements. Each branch of the tree has a series of dots, and a BRREAM credit/credits award at the far end of the branch. Each of these dots represents a single criterion; to earn the BREEAM credit award, all of the criteria within the branch need to be met.

The data requirement is added by the user, as the Rule Engine cannot determine whether this requirement is correct or not. However, the user does not need to provide an overall, definitive evaluation; instead, he can input more meaningful information that can be helpful in effectively proceeding with the compliance checking. The data input takes the form of numerical values or a (True/False) decision; with the systems compliance check of POL1 completed, the results were compared with a manual assessment using the data in the BIM.

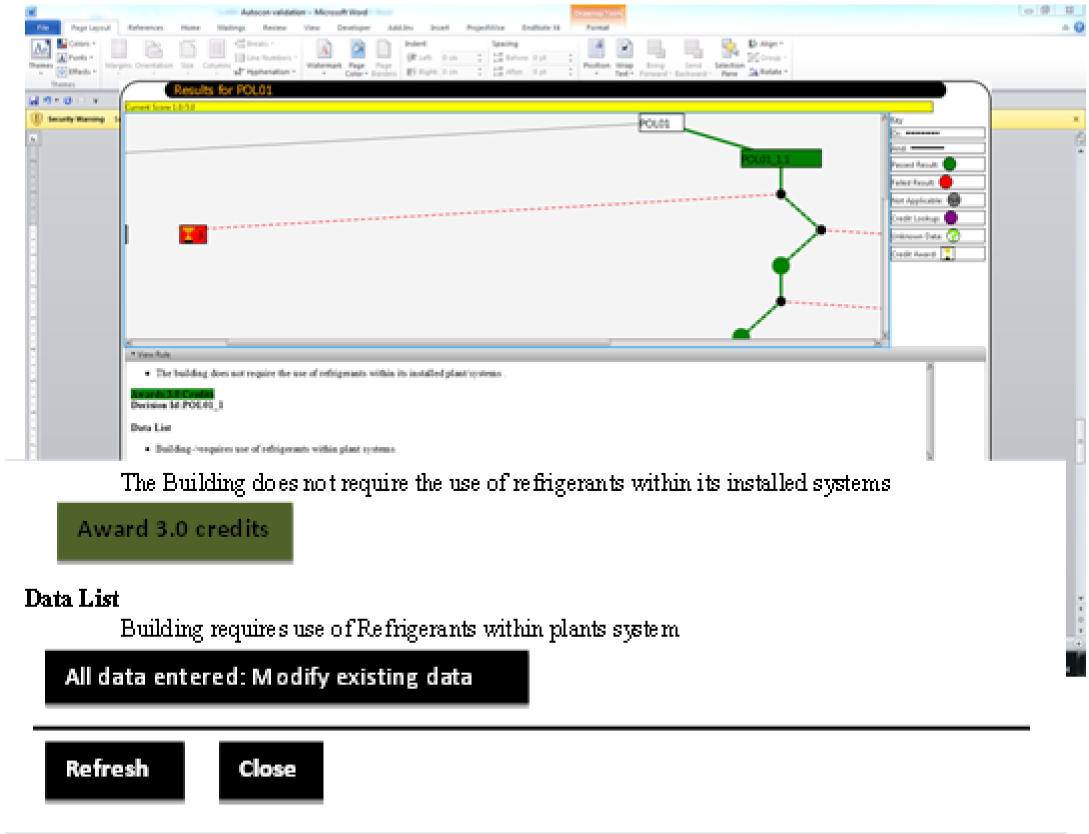

Figure 7-5 Details of results viewer: failure of 3 credits awarded

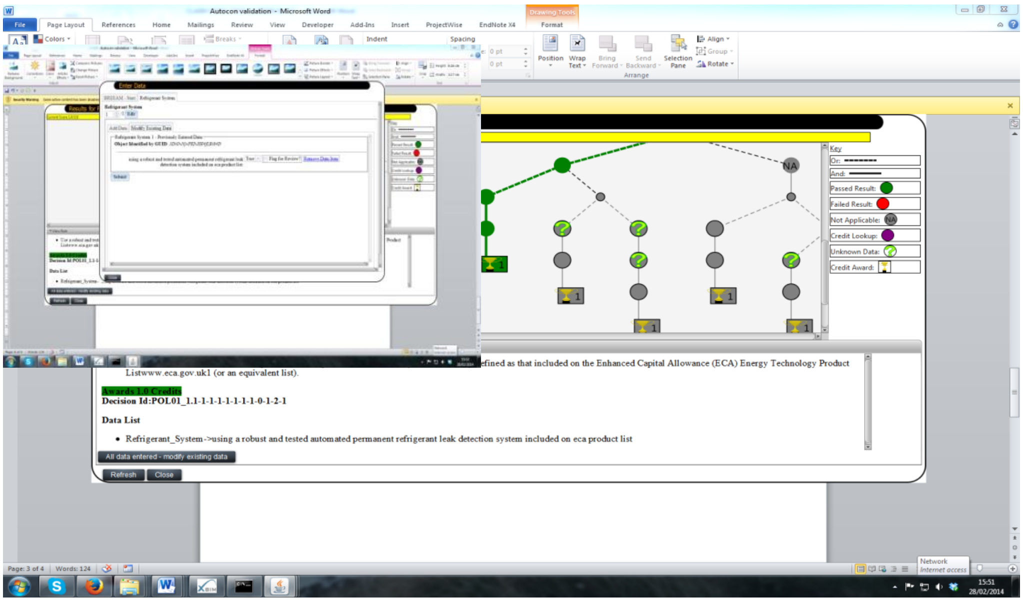

Figure 7-6 Details of results viewer: 1 Credit is awarded

To this end, it can be concluded that only a limited amount of data could be extracted from the Monument BIM model. The BREEAM *Pollution* issue 01 (Impact of refrigerants) was assessed; most of the compliance requirements were added to the system, because these data were lacking in the model. With the user engagement to add the required data, the rules engine processes the compliance requirements, and the results were reliable and consistent with the results obtained from the manual assessment process. A more-detailed case study is given in the following section.

7.2 Case Study (2) The Orthopaedic Hospital in Cardiff bay

7.2.1 About the project

This section describes the design of the Orthopaedic Hospital in Cardiff bay, and explores the possibility of applying the automated compliance checking tool to gain a higher BREEAM rating.

In 2013, a design team from Cardiff University developed an integrated building design project for a new Orthopaedic hospital in Cardiff. The new hospital was to be constructed in a largely-public place in Cardiff Bay.

Sustainability both during the construction phase and lifecycle of the project was a crucially- important issue throughout the design process. It was therefore integrated into the design by all disciplines, and was achieved through maximising the specifications of the building.

A variety of measures were incorporated in the design, with the purpose of achieving BREEAM credits. The orientation and the shape of the new hospital were designed for maximum energy efficiency. The design also opened up at least 80% of public floor area to views, and incorporated patient areas with a 3% daylight factor. In order to optimise the energy consumption of the building, IES VE thermal simulations were used during the design process; as a result, windows and the corresponding natural lighting were optimised.

A BREEAM assessment has been conducted by the design team, and the proposed design features have been assessed to achieve the BREEAM 'excellent' rating. This is an integrated building project, which has been designed by implementing the BIM workflow to bring together information from every aspect of hospital design, from structural work to electrical systems. Users were able to work on local models simultaneously, and using the link function, they could automatically update the central model.

All modelling components were developed using Autodesk Revit - Figure 7-7 shows the architectural design of building. The software generates IFC files directly which is eventually used for automated compliance checking.

As already mentioned, the proposal incorporated a variety of sustainability features in order to respond to the BREEAM requirements. The majority of these features were assessable without the involvement of a certified BREEAM assessor. However, there are a few issues where the assessment would require the use of the official BREEAM supporting tools. In these cases, the design team has assumed that related features meet the BREEAM requirements, and that the targeted BREEAM credits are achieved - for example, the environmental impact of ecological features.

The automated compliance checking implementation promotes efficient designs and construction of buildings. A design team can initially set their sustainable design targets (i.e. BREEAM requirements), and identify the design features according to the previously-set target. Then, compliance checking can be done dynamically as the design develops, giving the chance for modifications and enhancements.

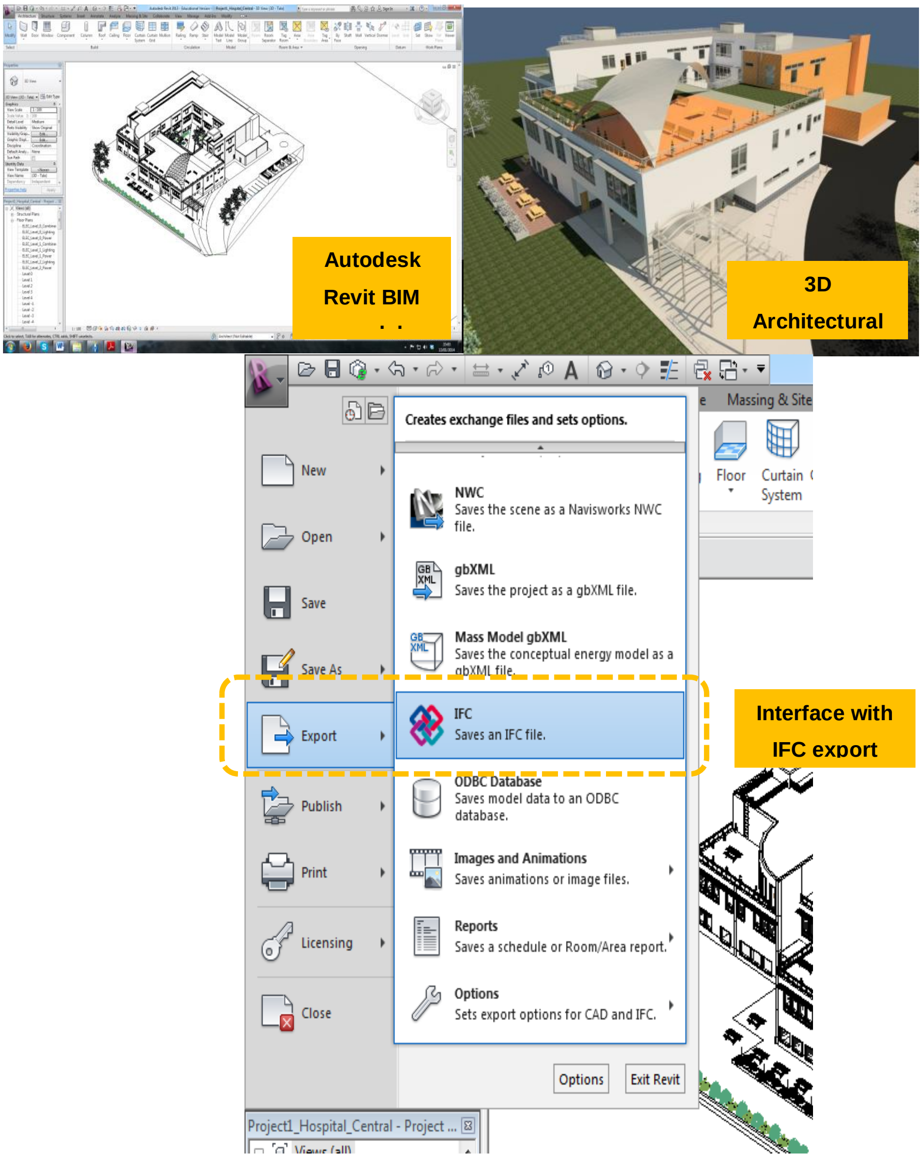

Figure 7-7 Orthopaedic Hospital design using Autodesk Revit Design

Most BIM authoring tools are able to populate the IFC data model from BIM. In this case, the data the Revit model has been exported to an IFC data model - shown in Figure 7-7. The generated IFC file shown in Figure 7-8 was very large in size, therefore, some data has been removed to minimise the size and to facilitate handling the data model. For this purpose, Solibri IFC Optimizer has been used.

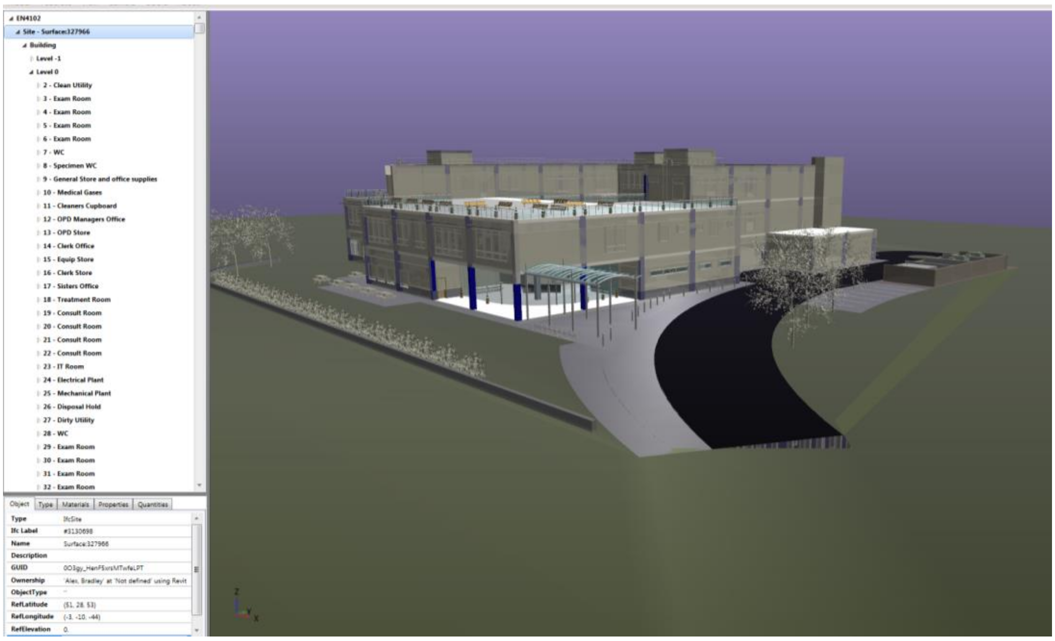

Figure 7-8 Orthopaedic Hospital design using IFC viewer XBIM

7.2.2 BREEAM assessment

A provisional BREEAM assessment has been conducted to the building according to the proposed design features and building functionally. Several assumptions were made to meet some BREEAM requirements. For example, some design evidences and documentations were assumed to be provided to earn the relevant BREEAM credits. A pre- Construction BREEAM assessment results are summarised in Table 7-1. The table illustrates the enumeration of BREEAM categories and the available / achieved number of credits towards each category. The weighting of each category is also calculated as indicated in the BREEAM requirements for hospital buildings.

Table 7-1 BREEAM assessment results

BREEAM Category	Credits Achieved	Credits Available	% of Credits Achieved	Category Weighting %	Category Score
Management	22	22	100.00%	0.12	12.00%
Health and Wellbeing	14	15	93.33%	0.15	14.00%
Energy	8	31	25.81%	0.19	4.90%
Transport	7	11	63.64%	0.08	5.09%
Water	7	9	77.78%	0.06	4.67%
Materials	4	13	30.77%	0.125	3.85%
Waste	7	7	100.00%	0.075	7.50%
Land Use and Ecology	6	11	54.55%	0.1	5.45%
Pollution	11	13	84.62%	0.1	8.46%
Innovation	5	10	50.00%	0.1	5.00%
Final BREEAM score				70.92%	
BREEAM Rating				EXCELLENT	

By implementing the automatic complince checking system, an attempt is made to compare the results from the manual assessment summarised in Table 7-1 with that obtained by the developed tool for BREEAM categories, as follows:

1) Management

Considering the management issue, the current design of the Orthopaedic Hospital complies with all BREEAM 'excellent' management requirements. The design obtained 100% of the managements credits, based on the available 22 BREEAM credits.

By implementing the develoed tool to check for compliance, all of the data related to construction management were added by the user. The IFC file could not provide direct responses to the management requirements, as stated in BREEAM. Figure 7-10 demonstrates the user interface, where a criteria needs to be met for every sub-category of the BREEAM-Management issue. Each criterion is set as a Boolean statement for the user to handle, and the achieved number of credits is provided in the results pane. This allows the user to continuously review the results if any change to the data happens.

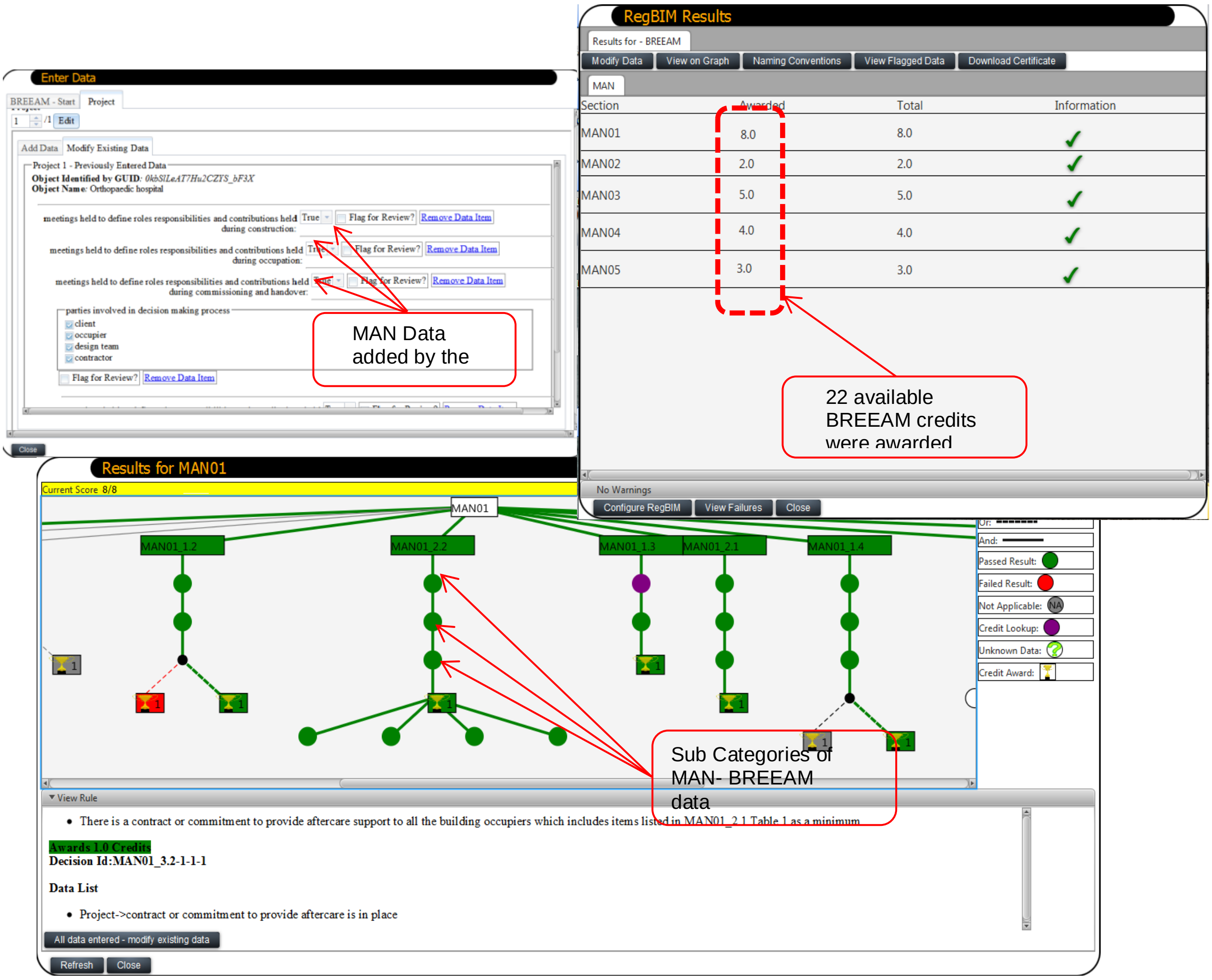

Figure 7-9 BREEAM- Management issue testing

Most of the BREEAM requirements concerning the sustainable management of the building design are subjective; this information can seldom be presented by the information model.

2) Health and Wellbeing

By implementing the developed tool to asses Hea–BREEAM, it has been determined that there are several complicated assessment measures. Health and wellbeing measures are associated with compliance with other standards and regulations, for example lighting design and noise levels. Although at the current stage of the software implementation, most of the data are added by the users, there is still information that could be considered for direct extraction from the BIM model. Figure 7-10 illustrates some requirements that could be directly- extracted from the BIM model, such as space dimensions (room depth and window size). Similarly, the following aspects can be extracted from BIM

- Daylight features of the building and the percentage of areas that are exposed to daylight
- Lux ratings for luminaries and the percentage of floor area location of controls for heating
- Lighting and cooling, such as zoning for lighting and heating
- Specifications for fixtures and fittings (e.g. taps, toilets *etc.*) view out (distance from window).

The BIM model can provide this information, but it is difficult to automate extracting the data for an automated compliance checking process.

Compared with manual assessment, there are 15 Hea-BREEAM credits for healthcare buildings. The manual assessment obtains 14 credits, while only 12 credits were awarded based on the automated assessment process, even when the data was added manually by the user. The system could not process some of the information, because there was information missing elsewhere that needs to be dealt with.

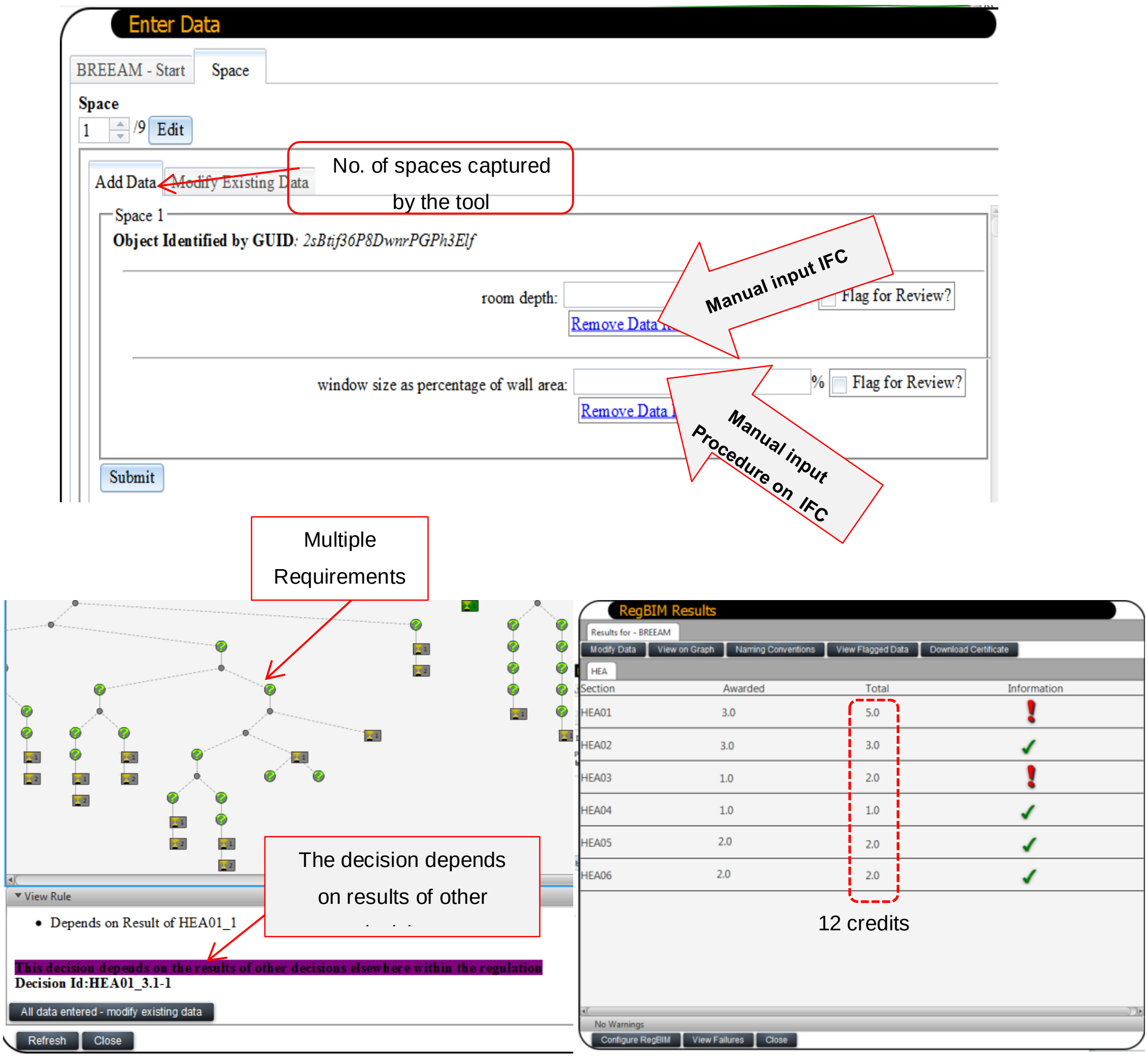

Figure 7-10 BREEAM- Health and wellbeing issue testing

3) Energy

Assessing the BREEAM energy performance of the Orthopaedic Hospital building using the developed tool provides similar results to the manual process; 8 BREEAM credits have been awarded according to the added data. Again, a large amount of data was added by the user, nevertheless, there is significant potential to automate extracting energy data from energy simulation tools. Figure 7-11 summarises the final results.

Figure 7-11 Energy issue assessment Results

4) Transport

The aim of the BREEAM-Transport assessment is to reduce transport-related pollution and congestion, and to encourage and reward a building that is located in close proximity to local amenities. The assessment comprises the features of building locations, along with the availability of adequate cyclist and pedestrians facilities. For example, to meet the requirements of Transport 2 – 'Proximity to amenities': the building must be within 500 m of the following amenities: a. Grocery shop and/or food outlet, b. Post box, c. Cash machine, d. Pharmacy. BIM modelling can access this data once it is integrated with geographic information system (GIS) facilities. For the current design of the Orthopaedic Hospital, it has been determined that the building location met these requirements - this is shown in Figure 7-12. At present, this data must be added manually by the user to the automatic checking tool; the tool processes the added data, and reports similar results to the manual assessment process.

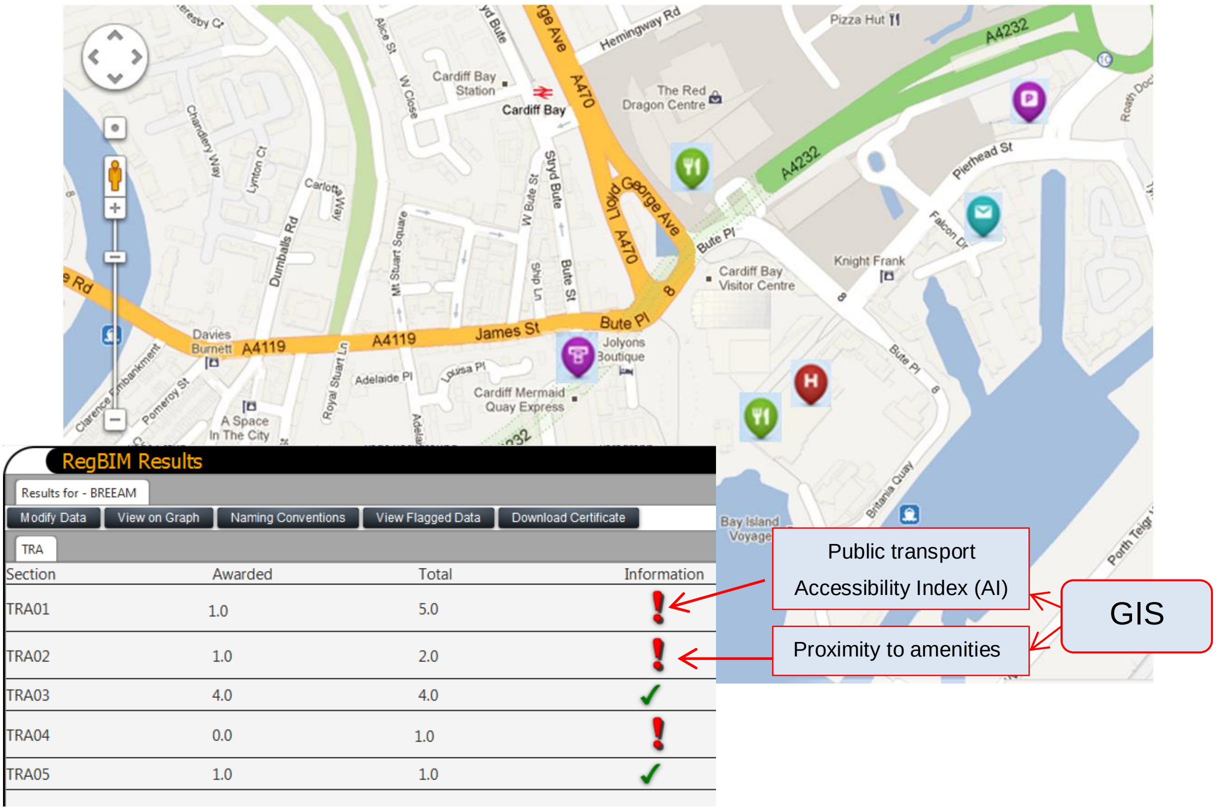

Figure 7-12 Proximity to amenities a. Grocery shop and/or food outlet, b. Post box, c. Cash machine, d. Pharmacy

Potentially, by integrating the developed tool with GIS, the distances between the building model and the amenities defined by BREEAM could be calculated. That would automate the assessment of the relevant criteria. A simple procedure that compares the calculated distance against the BREEAM requirement could be defined for the Rule Engine to process; to that end, designers might allocate areas for new amenities within their design, to achieve a desired credit.

5) Water

BREEAM water assessment has been set to improve the sustainable usage of water. The scheme credits a building that implements water efficacy systems such as leak detection systems, water monitoring, water consumption controllers and water-efficient equipment. The IFC data model defines every distribution system within the design. In addition, every piece of equipment defined in IFC has its specification attached to the object definition, hence most of the data needed for the BREEAM – water assessment can be provided by BIM. Although the compliance checking system can capture the availability of some elements such as controllers or valves, the data definition does not always comply with BREEAM requirements. In implementing the developed tool, only (4) credits were achieved, while 6 credits were achieved through the manual assessment. A preliminary assumption has been made during the manual assessment, and the credits in the manual assessment depend on an assumption, while the tool needed more information to complete the process -this is shown in Figure 7-13.

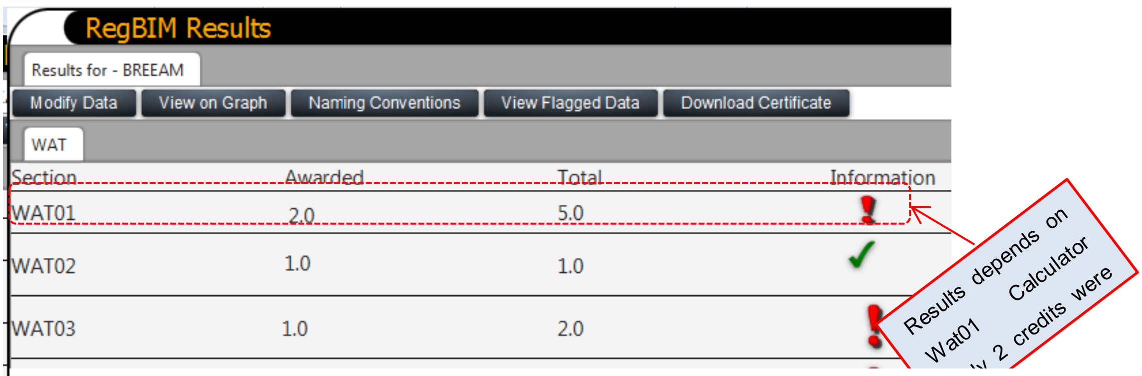

Figure 7-13 BREEAM- Health and wellbeing issue testing

6) Materials

The BREEAM materials assessment is set to encourage the use of sustainable construction materials, with low environmental impact over the building's life cycle. The assessment comprises testing the robustness of building elements to minimise the frequency of replacement and maximise materials optimization. Specifications of construction materials are attached to the individual building element as part of the configuration of the IFC data model; nevertheless, BREEAM requirements are neglected in the current IFC.

The BREEAM materials Mat 01 assessment is conducted using ‘The Green Guide’. It is part of the BREEAM assessment process to provide a simple 'green guide' to the environmental impacts of building materials, based on numerical data. This data is set out as an A+ to E ranking system, where A+ represents the best environmental performance or least environmental impact, and E the worst environmental performance or most environmental impact. The environmental rankings of construction materials are based on Life Cycle Assessments (LCA) (Ortiz et al., 2009); this numerical representation of materials’ environmental impact could potentially be embedded into the compliance checking system. Currently, the developed tool cannot award BREEAM credits to the Mat 01 sub-category, since the relevant calculator has not been used for the assessment, as illustrated in Figure 7-14.

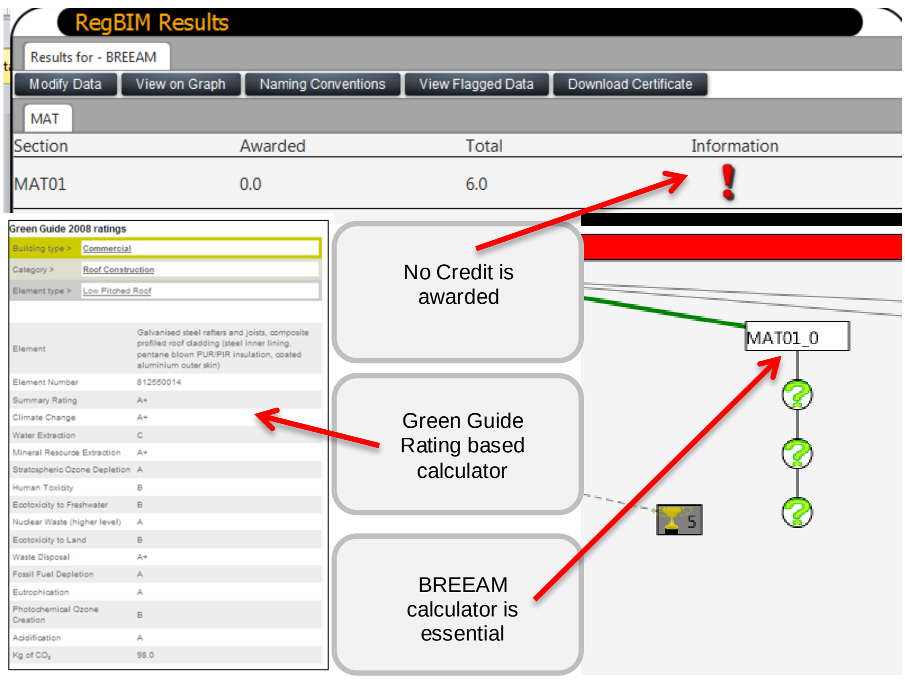

Figure 7-14 BREEAM- Material issue testing

7) Waste

The aim of the BREEAM-Waste assessment is to mitigate the construction waste impact of buildings. A building can be awarded BREEAM credits if recycled and secondary construction materials are used, thereby reducing the need for virgin materials, and reducing waste. The specifications of construction materials are well-defined in the IFC data model. The quantities of recycled materials can also be provided by the BIM model. BREEAM-Waste assessment also considers the availability of adequate waste storage facilities for a building's operational–related waste stream. By implementing the tool, similar results to the manual assessment process are reported - this is shown in Figure 7-15. The data added to the tool is extracted from the BIM model manually, at the current stage of the development.

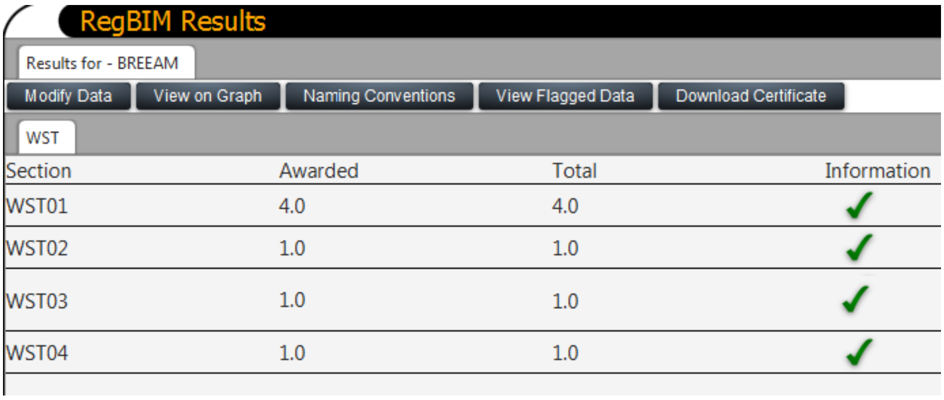

Figure 7-15 BREEAM- Waste issue testing results

8) Land Use and Ecology

Most of the data needed for BREEAM-Land use and ecology are obtained from external data sources, and is not necessarily present in the BIM model. For example, BREEAM awards a credit to a building if an ecologist has been appointed to verify the ecological value of the construction site, and its long-term impact on the biodiversity of the surrounding areas. All of the relevant data for the Orthopaedic Hospital was added to the tool; values for the majority of this data were assumed by the design team. The Rules Engine processed the added data, and reported similar results to the manual assessment process. This is shown in Figure 7-16.

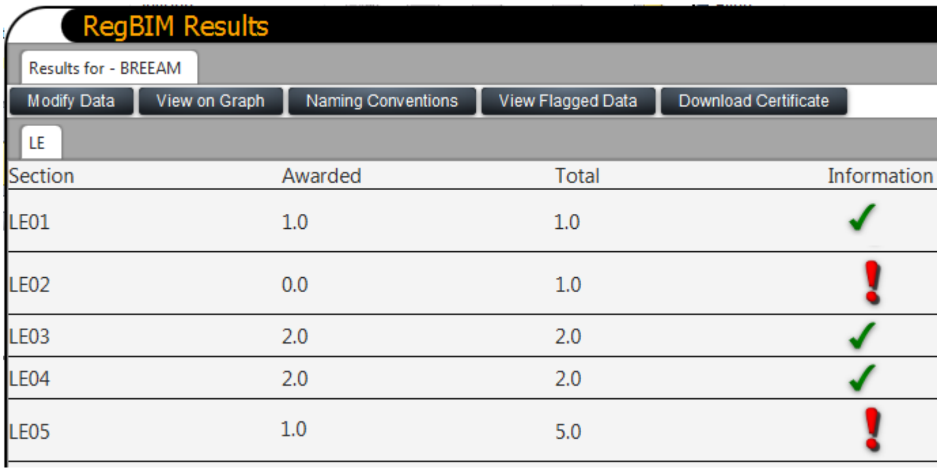

Figure 7-16 BREEAM- Health and wellbeing issue testing

9) Pollution

The BREEAM-pollution assessment is set to minimise the pollution that is caused by buildings. This includes mitigating the impact of greenhouse gas emissions, reducing unnecessary light and noise pollution, and encouraging the supply of heat from a system, with minimum NO_x emissions. The assessment relies on the specification of distribution systems inside the building, such as ‘refrigeration system’, and the attached components to the systems such as leak detection devises, noise dumpers *etc*. While looking for the relevant data in the IFC data model, it has been noticed that most of the required information is present in the BIM model, however, the information is fragmented and is very difficult to extract directly from the data model. All of the orthopaedic hospital pollution-related data has been added to the tool, and similar results to the manual assessment process have been reported - the results are demonstrated in Figure 7-17.

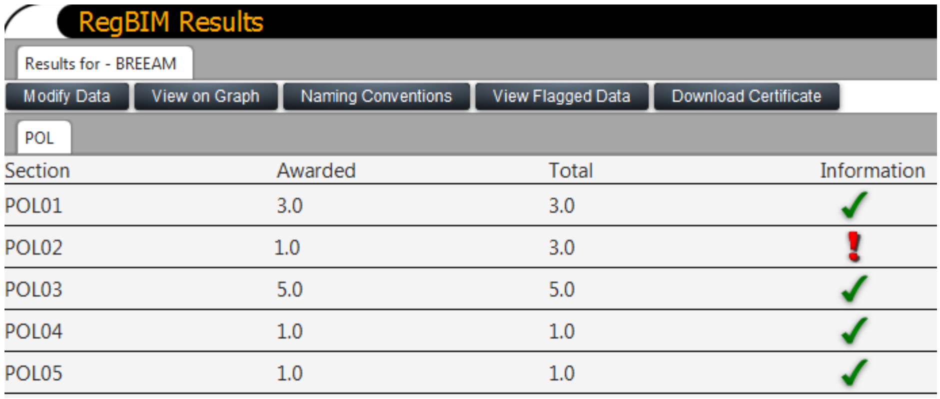

Figure 7-17 BREEAM- Health and wellbeing issue testing

10) Innovation

There are additional credits, called 'innovation' credits, available for the recognition of sustainability-related benefits or performance levels; these are currently not recognised by standard BREEAM assessment issues and criteria. In the hospital design, five out of the ten 'innovation' credits available are thought to be achievable, therefore this has been assumed for both the manual assessment and the rules-based approach.

7.3 Summary and results discussion

By implementing the Developed tool to check BREEAM compliance for a previously-assessed building using the traditional method, consistent results were obtained on several occasions, while different results were reported in other places. The similar results were found because the data added to the software tool was similar to the data used for the traditional assessment. The Rule Engine of the proposed system processes the IFC data to check compliance with the pre-defined rules that are stored in the system, and the final results are reported. The results are shown in Figure 7-18, along with the rules that are achievable. The tool provides the user with the final BREEAM rating dynamically, as the BREEAM credits are added. Hence, the user can be aware of the impact that changes in the design features have on the sustainability performance of the building. For example, if the orientation of the building is changed, the building's energy performance will be influenced, which will lead to a change to the number of the awarded BREEAM- Ene credits, and hence the final BREEAM rating will be affected accordingly.

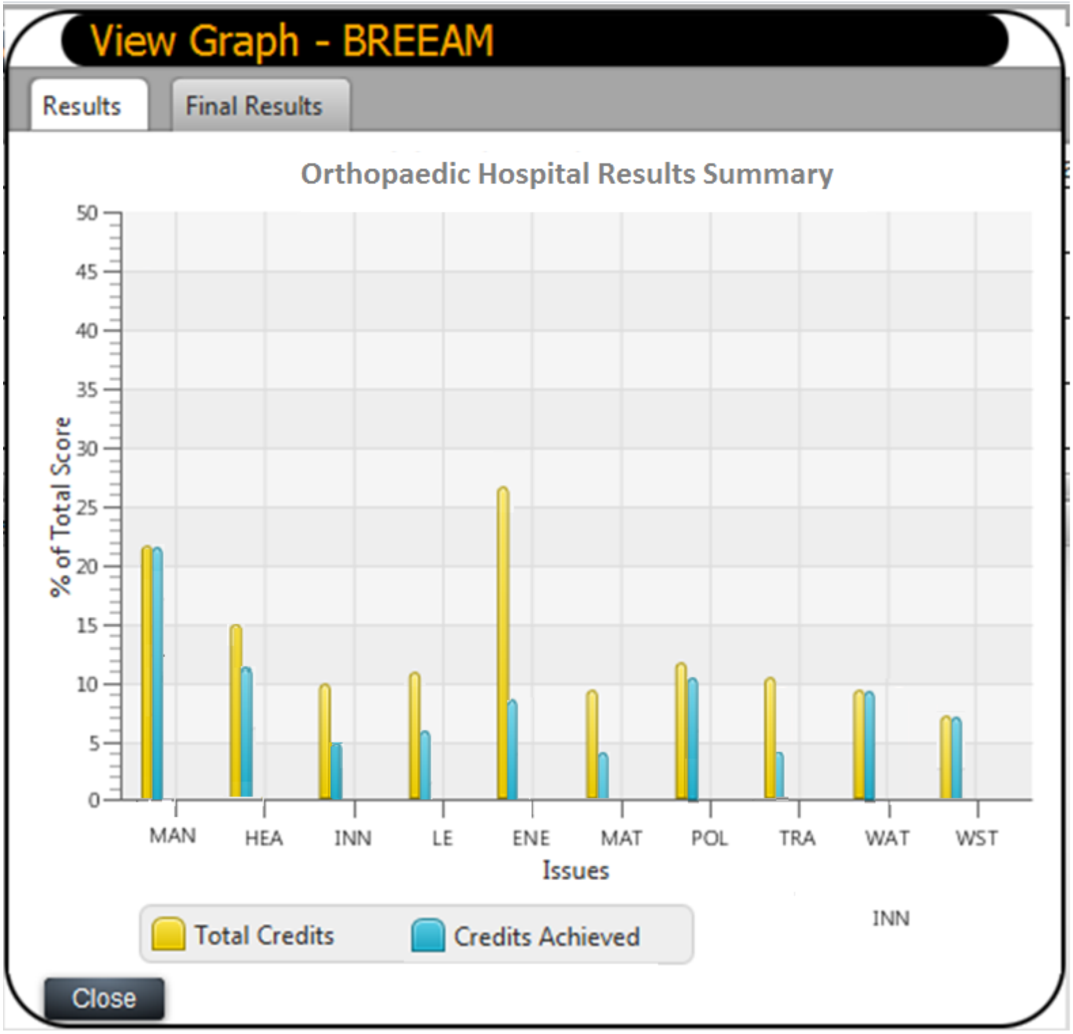

Figure 7-18 BREEAM Assessment Results

A comparison of the results between the traditional assessment method and BREEAM compliance checking, using the tool is summarised in Table 7-2. An 'Excellent' BREEAM performance was reported using the manual assessment, while only a 'Very Good' BREEAM rating is obtained using the software tool. This variation in results is due to the fact that the rules engine cannot proceed in checking a criterion which is dependent on other requirements, unless these requirements are met. This especially occurs when BREEAM scales some issues using a specific calculator. With the manual preliminary assessment, assumptions could be made to proceed with the next criteria.

Table 7-2 Comparative results for BREEAM assessment

BREEAM Category	Credits Available	Credits Achieved Manual assessment	Credits Achieved Using the tool	Category Weighting %	Category Score	Automatic checking Category score
Management	22	22	22	0.12	12.00%	12.00%
Health and Wellbeing	15	14	12	0.15	14.00%	12.00%
Energy	31	8	8	0.19	4.90%	4.90%
Transport	11	7	7	0.08	5.09%	5.09%
Water	9	7	4	0.06	4.67%	2.60%
Materials	13	4	4	0.125	3.85%	3.85%
Waste	7	7	7	0.075	7.50%	7.50%
Land Use and Ecology	11	6	6	0.1	5.45%	5.45%
Pollution	13	11	11	0.1	8.46%	8.46%
Innovation	10	5	5	0.1	5.00%	5.00%
Final BREEAM score				70.92%		66.31
BREEAM Rating				EXCELLENT		Very Good

BREEAM Compliance checking using the developed tool reveals the current situation of IFC, with poor representation of information concerning sustainability features of the building design. The initial aim was to develop an automated compliance checking system that is able to extract sustainability requirements from the BIM model. This direct extraction of data, however, proved very difficult to achieve at the current stage. The majority of the data was added by the user to proceed with validating the system. It is practically evident that the IFC comprises all of the building objects which are part of the compliance checking assessment process; however, the object's properties are not explicitly-described in the IFC file, to fulfil the compliance requirements.

Relying on the user engagement, the developed system correctly calculates the results, as judged by a comparison with the traditional assessment method.

The rules execution is carried out as a repetitive process; there are no significant concerns about the volume of knowledge that the Rule Engine needs to process; its operational performance remains the same whether the rule base has ten or ten thousand rules. In terms of scalability and rules-efficiency, the current approach allows the rules to be extracted and generated rapidly and efficiently. The rules are represented in a form understood by construction domain specialists, without requiring knowledge of IFC data file formats or any underlying rule engine.

7.4 Technical Issues of System Implementation

Implementing the tool to check BREEAM compliance of the Orthopedic Hospital building provided similar results to the manual assessment procedure, except for the cases that were explained earlier. Nevertheless, there were some technical issues and errors which have been resolved during the validation process. Figure 7-19 shows a screenshot of some errors caused by wrong data input to the system's dictionary.

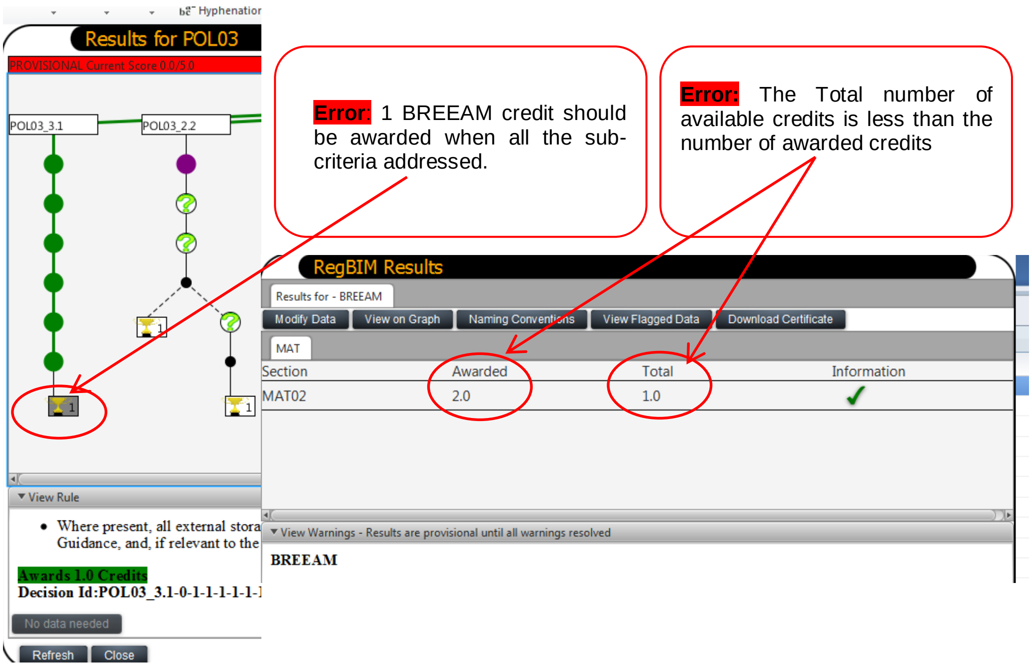

Figure 7-19 Some errors during system implementation

Several system errors were also detected during the validation process; most of these software failures occurred due to bugs in the code, and problems between the host and the storage medium. Figure 7-20 gives screen shot examples of the handled issues.

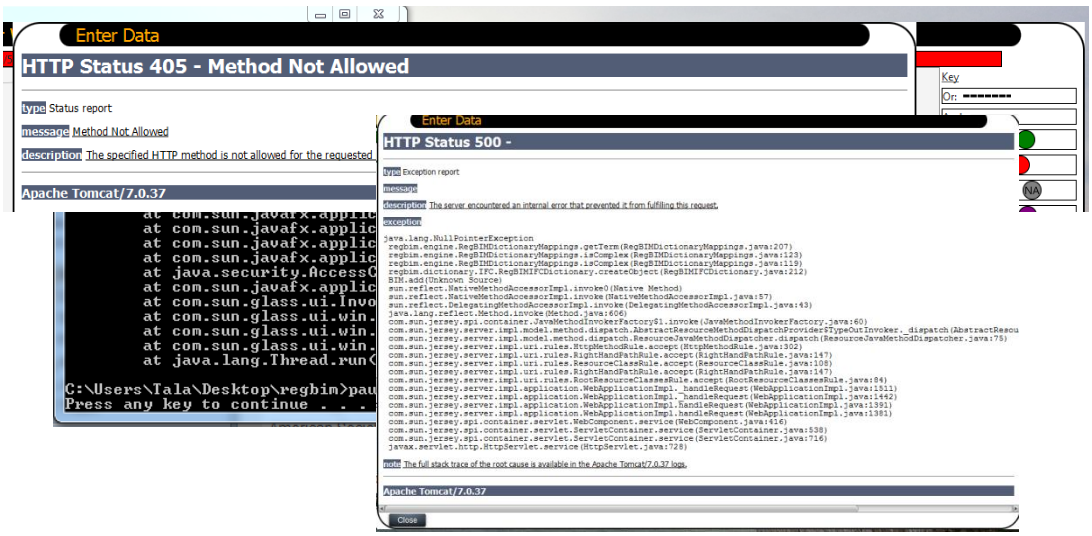

Figure 7-20 System errors

7.5 Implementation

The rule-based system was then integrated in the form of a plug-in with an industry standard design package. Bentley Microstation (AECOSim) was targeted for the initial implementation, as illustrated in Figure 7-21, however, the approach is generic so that a similar plug-in for Autodesk Revit could easily be created, for example.

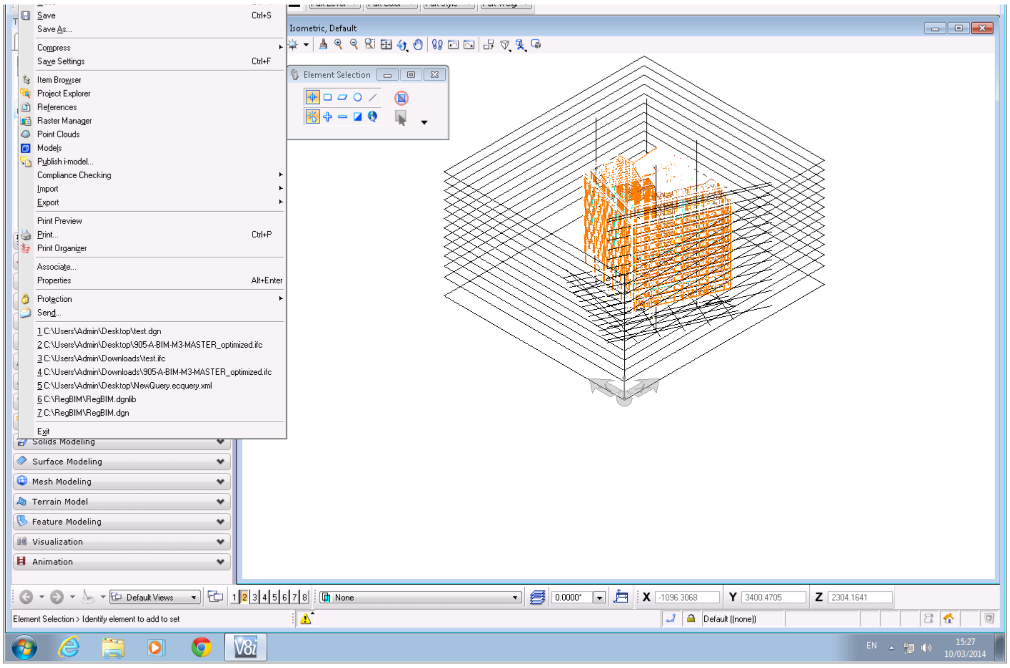

Figure 7-21 Plug in to Bentley systems

This ability to integrate a regulatory compliance system together with design tools has many advantages for designers: It allows them to visualize and preview the sustainability performance of a building and its regulatory compliance during the modelling phase, enabling them to achieve the optimized design.

In addition to this, the author believes that it can reduce the design time and costs, and release human assessors from such a repetitive and tedious task.

7.6 Conclusion

The validation conducted in the previous sections has shown that the regulatory compliance system, developed using the proposed methodology, is valid and reliable. The developed system correctly calculates results, as judged by a comparison with the traditional assessment method. From the designer’s view point, the system exhibits potential savings in time, in terms of verifying compliance, if system were to be developed further. The developed tool could be particularly useful in the time consuming elements of materials selection and measurement, recycled content and responsible sourcing. It was not possible to quantify these potential savings at this stage, because of the early development status of the system.

Nevertheless, the system implementation reveals that the current IFC data model lacks representation of certain domains of data. This thesis targets the domain of environmental sustainability, where the deficiency of the IFC determined. Although a complete list of data has been proposed to enhance the current IFC, and to make it efficiently compliant with the domain of compliance checking, the implementation has not yet been achieved. The semi- automated compliance checking procedure still needs the user engagement. The user role is to enrich the objects definitions within the BIM model, with detailed attributes to establish a comprehensive domain-compliant BIM model for automated checking.

The current level of development of BIM appears to lack the necessary maturity to make immediate the use of the automatic compliance checking tool and similar solutions.

However, initiatives like this should help to focus developers on the areas where useful information is actually required. Currently, the ‘double-handling’ of information (electronic compliance checking and human assessment) is required in order to conduct the assessment. Nevertheless, further efforts could enhance the development to be an effective solution for automated sustainability compliance checking.

Chapter 8

BIM Level Three: The Use of Ontology to Extract Data from IFC for Automated Compliance Checking

This chapter introduces the concept of use of the semantic web, and of engineering ontologies, as an enhancement to the rules-based approach in the compliance checking process. In this chapter, an ontology development methodology is described in Section 8.1, and a BREEAM taxonomy for ontology applications is described in Section 8.2. A description of IFC OWL and the current maturity level is given in Section 8.3, and finally, implementation examples and implementation results and discussions are given in Sections 8.4 and 8.5, respectively.

8.0 Introduction

The term ‘ontology’ originates in the Greek ‘ontos’ for being and ‘logos’ for word. This word has been used by German philosophers in the 19th century ‘to distinguish between the study of being as such from the study of various kinds of being in natural science’ (Turk, 2006). Bunage (Amor et al., 2002) defines ontology as a way to orderly organize the world - the author describe ontologies as ‘the furniture of the world’. In computer science, the term ontology has been introduced to define ‘what exists’ for collaborating agents (McGuire et al., 1993). The most-referenced ontology definition available in the literature is that presented by Gruber as “an explicit specification of a conceptualization” (Gruber, 1993). The author elaborates the definition as ‘explicit formal specifications of terms in the domain and the relationship among them’.

The term *‘specification’* refers to the representative vocabulary such as classes and relations. This vocabulary provides formal meanings to the constraints on their coherent use within the domain, while the term ‘*conceptualization’* refers to ‘concepts, relationships, and other distinctions that are relevant for modelling a domain’(Gruber, 1993). The addition of the term ‘ontology’ into the vocabulary of construction informatics is fairly recent; the term ‘conceptual model’ was used for some time before the emergence of engineering ontologies. The research studies on ontologies and conceptual models result in very similar outcomes, and there seems to be only a fine line between the two terms (Welty and Guarino, 2001).
‘Taxonomy and classification’ have similar a relationship as that between ‘ontology and conceptual model’. Taxonomy has been defined by The Oxford Dictionary of Science as ‘the study of the theory, practice, and rules of classification’, while the term ‘classification’ has been defined as ‘systematic arrangement in groups or categories according to established criteria’. Taxonomies are a vital element in establishing a conceptual model, because they provide a way of organizing different concepts. Classification, on the other hand, can shape the hierarchy of the conceptual model. Ontology can provide the baseline for both process and product modelling, as well as for a classification system to present knowledge, which is not only used by

computer systems, but also by humans (Uschold and Jasper, 1999). In order to establish a knowledge-base system, it is essential to decide which knowledge presentation technique is appropriate to fulfil the requirements of a system. ontology is one such system, in addition to numerous artificial intelligence techniques available, such as the previously-mentioned rule-based expert system, frame-based systems, fuzzy systems and artificial neural networks (Negnevitsky, 2005). In recent years, the harness capacity of engineering ontologies outshine the top of Knowledge representation systems list in AEC/FM sectors (Rezgui et al., 2011).

Ontologies have been extensively and profitably employed in sectors outside engineering, for example the websites such as Yahoo and Amazon. Ontologies have also been employed to structure knowledge about processes, products, activities *etc.* (Plessers and De Troyer, 2004). Within the field of compliance checking, Xiao, Cruz et all. have conducted a research study to deploy ontology to extract norms from electronic regulations. The researchers utilized SPARQL (Protocol and RDF Query Language) to formalize a query in terms of IFC model. The researchers check compliance by matching SPARQL to an RDF (Resource Description Framework data representation) (Xiao et al., 2004).

Pauwels, De Meyer et al. 2011 have investigated methodologies to establish semantic web-based approaches and semantic rules, for building performance checking. The researchers used N3-logic as a rules language to outline the logic in regulations. With the emergence of BIM technologies, many researchers have focused on implementing the concept of ontologies, together with the BIM/IFC data model, and to develop an ontology framework to access IFC model data (Pauwels et al., 2011, Katranuschkov et al., 2003). Beetz, Van Leeuwen et al. have explored the potential of connecting the Semantic Web initiative to the ‘domain of product data exchange’. The study focuses on presenting a semi-automatic way for elevating IFC data - presented by the EXPRESS schema - to an ontological level. The research is based on the available methods and algorithms emerging in the field of the inter-operability of knowledge representation. The researchers have stated that ontology compartmentalization has the potential to configure and reduce the complexity of the information representation of the IFC data model (Beetz et al., 2009). Within that context, other researchers have described a methodology for developing an ontology for the Low-Carbon domain. For the development of the ontology, the researchers relied on the ‘construction industry standard taxonomy (IFC)’. The IFC data model was enriched and expanded with concepts extracted from sustainability and low-carbon-oriented documents; this was done using ‘information retrieval (tf-idf and Metric Clusters) techniques’. It is not possible to apply a reasoning mechanism to extract data from the IFC data model directly. (Li et al., 2010). The current IFC acts as a data repository to represent the information attached to every object within the building model; however, this data model has not been designed with a logical foundation to allow automatic extraction of data to fulfil certain requirements.

In the research presented in this thesis, the rules-based approach is used to establish an automated compliance checking system, with respect to the information provided by the BIM model. Using a rules-based approach within a BIM environment has been reported as an effective solution(Thomas H Beach, 2013a). The principle of deploying this approach comprises extracting computable rules from the regulation documents. These rules are then compared against the information produced by the BIM model. This comparison is done by utilizing a rule engine to execute the requirements for sustainability compliance checking. Although the methodology that has been developed, and the resulting BREEAM compliance checker, have both performed well, the aim of fully automating BIM-based sustainability compliance checking is currently difficult to achieve. This is due to the fact that many assessment data requirements cannot be obtained from a BIM model without human interaction. Although the objects of the design model are represented in the IFC, there it is evident that the rules engine can only capture the explicit data requirements from the IFC data model, and it is still difficult for the rules engine to deal with the implicit concepts. It also remains difficult to track and evaluate attributes of objects whose instances are themselves classes, embedded in the requirements for compliance checking (Zhong et al., 2012). The latter conclusion potentiates the use of the concept of engineering ontologies to use reasoning to capture the implicitly-represented data requirement within the BIM environment. Ontologies are largely used to present domain knowledge, and to allow data sharing and re-use. This principle of applying the semantic web approach is used to establish a domain ontology for the data needed for the BREEAM assessment process; it can be used for the mapping process with IFC OWL to facilitate automated sustainability compliance checking.

8.1 Ontology development methodology

This section attempts to explore additional methods to answer the question of how the required data can be extracted from a variety of data storage media - i.e. an IFC model. It explores the potential of defining a road-map for using engineering ontologies to extract implicit data from the IFC by using reasoning. The approach adopted is based on formalizing the exchange modules using an ontological backbone, and mapping them to the entities of an IFC data model, and their relations, attributes and functions. The following sections present a discussion of the potential application of the semantic web techniques to coordinate the entanglement of information within a certain domain (Noy and McGuinness, 2001).

The focus is on the bundle of information that is needed to examine buildings' compliance with sustainability standards. A prototype has been developed and applied to several examples, using the ontology editor 'Protégé'. 'Protégé's plug-in architecture can be adapted to build both simple and complex ontology-based applications. Developers can integrate the output of Protégé with rule systems or other problem solvers, to construct a wide range of intelligent systems' (University, 2014). This research is focussed on sustainability compliance requirements data, and the case study implemented in this chapter is based on BREEAM. Protégé and the web ontology language (OWL) are the tools that are used to present the required BREEAM knowledge in a structured and reasonably-usable way for the implementation presented here.

The framework for the ontology implementation process is simplified in Figure 8-1. The first step involves building a taxonomy for all of the data included in BREEAM; the BREEAM list of data was previously defined, as a result of using the conditional logical decision tree and RASE methodology- this is explained in Chapter five of this thesis. According to BREEAM list of data, a new taxonomy is created using Protégé and OWL; all of the main objects adopted in BREEAM are included in the new taxonomy, and the relationship between these objects is defined.

The OWL-DL database is established for the context of sustainability compliance requirements, and a generic query and reasoning algorithm are applied to this database, using defined competency questions as necessary. The system processes building information and checks compliance with regulations in an intelligent way, rather than the exhaustive manual method of traditional compliance checking procedures.

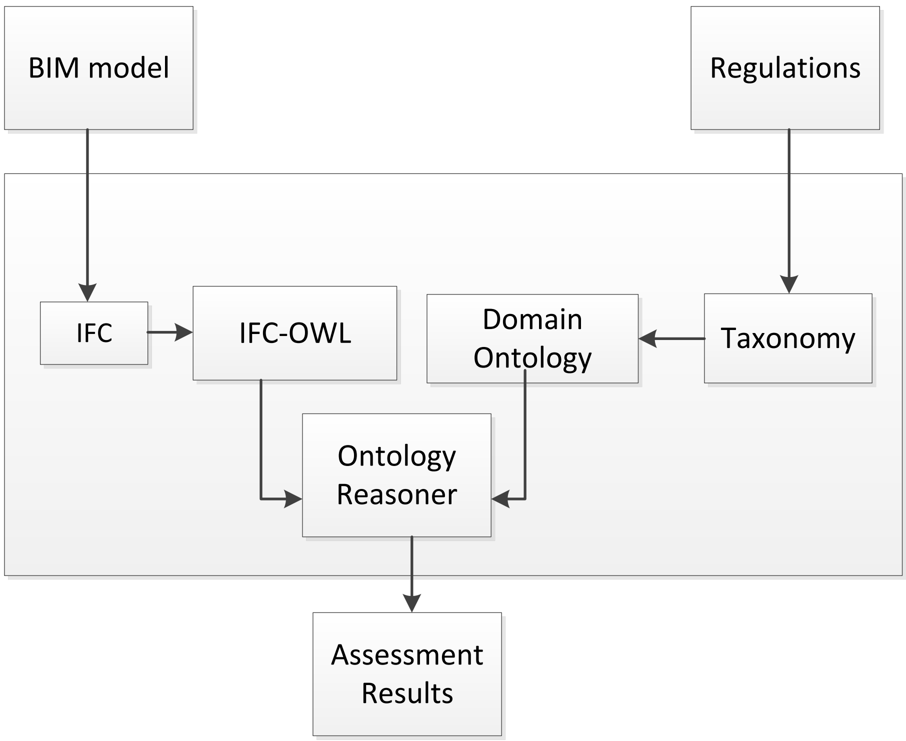

Figure 8-1 Ontology based assessment method

8.2 BREEAM taxonomy for Ontology application

This step involves the consideration of all terms used within the targeted regulation to construct a BREEAM ontology (Schevers and Drogemuller, 2005); these terms are identified in the form of objects, properties and requirements. A list of data requirements for compliance checking is summarized, and these classes are then re-formatted to form a taxonomy - the taxonomy is illustrated in Figure 8-2 This taxonomy is the backbone for compliance checking ontology (Svetel and Pejanovic, 2010), in which the criteria and compliance are formalised in OWL (Web Ontology Language).

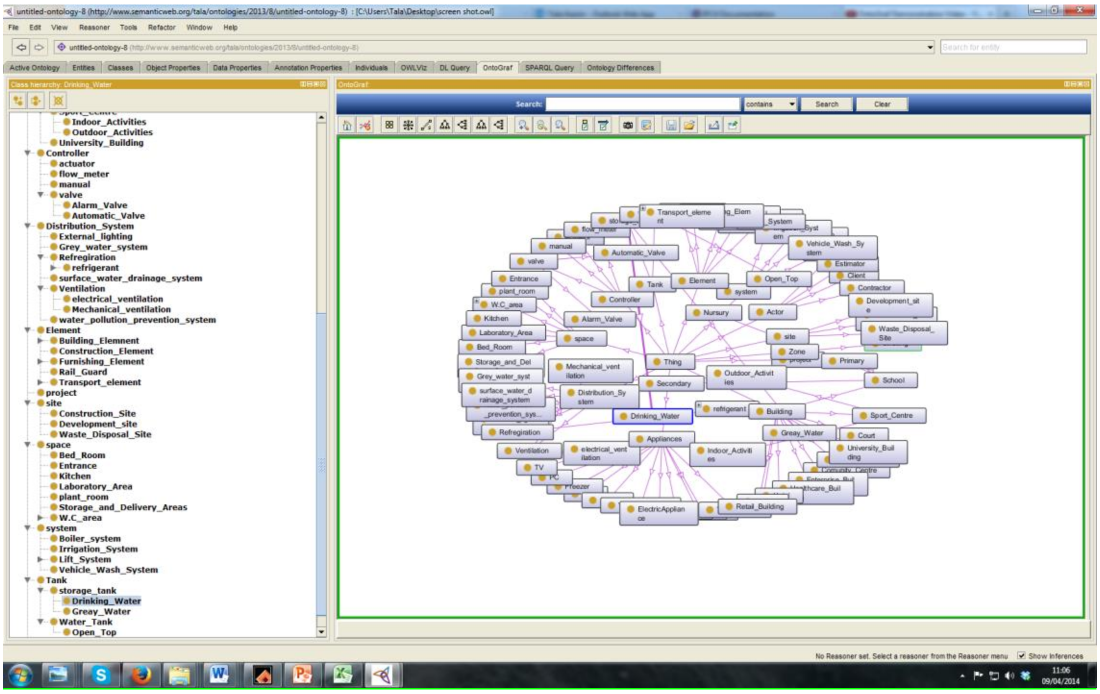

Figure 8-2 Taxonomy for BREEAM using protégé

8.3 IFC OWL

In general, the IFC data models already exhibit some basic requirements for ontology design. The IFC data model is intended as usable, sharable, reliable, and inter-operable formal specification. However, in the building and construction domain, to benefit from the full advantages of the IFC knowledge representation system, the data model and its population have to be transformed into a set of axioms, where reasoning capabilities can be applied (Katranuschkov et al., 2003). Many researchers have put considerable effort into implementing that transformation, and different approaches and methods can be found in the literature (El-Mekawy and Östman, 2010, Lima et al., 2005b, Schevers et al., 2007).

The IFC data model was originally written in an express schema, but it can be transformed into OWL; this transformation comprises generating a corresponding OWL class for each EXPRESS element, and converting each EXPRESS attribute into appropriate OWL properties *etc* - an example is given in Table 8-1. The current IFC is not sufficiently mature for fully-automatic conversion from the Express schema into OWL ontology. There are numerous challenges that make this transformation difficult, for example, there are certain types of semantics information that can be difficult to match to equivalent OWL classes, such as 'where' constraints of rules, and procedural 'function' calls. Within the field of sustainability compliance checking, the development of IFC OWL is pertinent to the development of the extended IFC that comprise all sustainability compliance checking data. The subsequent steps comprise using the IFC data model (IFC-OWL) for direct reasoning, with a defined

EAM OWL taxonomy

By exploring the IFC data model, it has been realised that all of the main building objects to be tested for compliance are included in the IFC data model. However, the pre-defined properties attached to these objects do not necessary fulfil the requirement for compliance checking. There are a plethora of characteristics and descriptive attributes which need to be added to the IFC data model, to establish the domain-compliant IFC ready for automated compliance checking. It is not within the scope of this thesis to develop a sustainability compliance model view of IFC OWL. However, such an ontological model view would have the potential to enhance the automatic compliance checking process by mapping the OWL model of any regulation i.e. BREEAM with IFC OWL of the relevant context.

Table 8-1 IFC express into OWL classes

IFC Entities	IFC Entities translated into OWL (Berners-Lee, 1998)
ENTITY IfcElement ABSTRACT SUPERTYPE OF (ONE OF (IfcBuildingElement) END_ENTITY; ENTITY IfcBuildingElement ABSTRACT SUPERTYPE OF (ONE OF (IfcDoor, IfcWall, IfcSlab, [...])) SUBTYPE OF (IfcBuildingElement) END_ENTITY; ENTITY IfcDoor SUBTYPE OF (IfcBuildingElement) END_ENTITY;	*:IfcElement a owl :Class; rdfs:subClassOf owl:Thing :IfcBuildingElement a owl :Class; rdfs:subClassOf : IfcElement; owl: disjointWith :IfcFurnishingElement :IfcDoor a owl :Class; rdfs:subClassOf : IfcElement; owl: disjointWith :IfcWall, :IfcWindow*

8.4 Implementation

Implementing the ontological approach to support automatic BREEAM assessment compliance checking is presented in this section. The criteria and BREEAM compliance requirements are formalised in OWL (Web Ontology Language). The proposed approach is illustrated with an assessment example taken from BREEAM assessor manual issue.

In the BREEAM Assessment manual, the following Table 8.2 demonstrates compliance:

Table 8-2 Assessment Criteria - Refrigeration

First Credit - Refrigerant leak detection
Systems using refrigerants are contained in a moderately air tight enclosure (or a mechanically ventilated plant room), and a refrigerant leak detection system is installed covering high risk parts of the plant.
Second Credit - Refrigerant recovery system
The automatic shutdown and pump down of refrigerant occurs on the detection of high concentrations of refrigerant in the plant room/enclosure. For the majority of cases only systems in mechanically ventilated/moderately air tight plant rooms (or enclosures) comply.

Notes:

Where CO2 is used as a refrigerant, the refrigerant recovery system credit/requirements can be awarded/met without the need for a recovery system;

In the BREEAM-ONTO ontology, the objects such as "Refrigeration Systems" and "Plant Room" in the compliance of these assessment criteria are represented in OWL format as follows:

$$< owl{:}Class\ rdf{:}ID = "Refrigeration" >$$

$$< owl{:}Class\ rdf{:}ID = "PlantRoom" >$$

The hierarchy of classes and sub-classes in ontology is represented using "subClassOf" in OWL; for instance, the class of Controller that involves four types of controllers in the building service system: Actuator, Flow Meter, Manual Controller and Valve. These four types of controllers are organised as sub-classes of the Controller class, which is the super-class. One of the sub-classes, the Valve, contains two types of valves that are 'Alarm Valve' and 'Automatic Insulation Valve' respectively. This three levels hierarchy is encoded in the form OWL as following::

$$< owl{:}Class\ rdf{:}about = "\#Valve" >$$

$$< rdfs{:}subClassOf\ rdf{:}resource = "\#Controller" >$$

...

$$< owl{:}Class\ rdf{:}ID = "AlarmValve" >$$

$$< rdfs{:}subClassOf >$$

$$< owl{:}Class\ rdf{:}about = "\#Valve" >$$

$$</rdfs{:}subClassOf >$$

$$</owl{:}Class >$$

Similarly, the instances (individuals) could be added into the ontology by following the same syntax. For example, in two assessment tasks presented in this section, there are two ‘Alarm Valves implemented in two different buildings, “AlarmValve_01” and “AlarmValve_02”, which are both instances of the class “AlarmValve”. In the OWL file, these two instance are represented as:

$$< AlarmValve\ rdf{:}ID = "AlarmValve\_01" >$$

$$< AlarmValve\ rdf{:}ID = "AlarmValve\_02" >$$

The relationships between these objects such as “used” in the compliance are defined as Object Property in OWL:

$$< owl{:}ObjectProperty\ rdf{:}ID = "isUsedBy" >$$

The Object Property provides the capability of defining relationships and restrictions on instance level in ontology. Taking the Alarm Valve in a Refrigeration system as an example, the Refrigeration is controlled by Alarm Valve in the building. Two objects “Refrigeration” and “Alarm Valve” are defined as “RefragerationSystem_01” and “AlarmValve_01” respectively, and connected with each other using a set of inverse Object Properties “isControlling” and “isControlledBy”. The following OWL illustrates the relationship between these two instances:

$$</owl{:}ObjectProperty >$$

$$< owl{:}ObjectProperty\ rdf{:}ID = "isControlledBy" >$$

$$< rdfs{:}range\ rdf{:}resource = "\#Valve"/>$$

$$< rdfs{:}domain\ rdf{:}resource = "\#Refrigeration"/>$$

$$< owl{:}inverseOf >$$

$$< owl{:}ObjectProperty\ rdf{:}ID = "isControlling"/>$$

$$</owl{:}inverseOf >$$

$$</owl{:}ObjectProperty >$$

...

$$</owl{:}ObjectProperty>$$

$$<owl{:}ObjectProperty\ rdf{:}about = "\#isControlling">$$

$$<owl{:}inverseOf\ rdf{:}resource = "\#isControlledBy"/>$$

$$<rdfs{:}domain\ rdf{:}resource = "\#Valve"/>$$

$$<rdfs{:}range\ rdf{:}resource = "\#Refrigeration"/>$$

$$</owl{:}ObjectProperty>$$

...

$$<isControlledBy>$$

$$<AlarmValve\ rdf{:}ID = "AlarmValve\_01">$$

$$<isControlling\ rdf{:}resourc = "\#Refrigeration\_System01>$$

$$</AlarmValve>$$

$$</isControlledBy>$$

In addition to the Object Property, there are another two types of properties used in ontology to represent attributes, and to provide information and description of classes or instances (individuals): Data Property and Annotation Property.

Figure 8-3 lists all of the classes, properties and instances of the BREEAM-ONTO ontology that is used in this case in Protégé 4.3.

After the ontology is created, axioms are necessary to add restrictions to classes and instances. These restrictions are produced from the description of building objects in the BREEAM Assessment Manual. There are several types of restrictions that Owl can provide; the axioms below show one of these restrictions to a class in the BREEAM-ONTO ontology:

$$Axiom\ 1{:}\ Refrigeration\ Use\ Max\ 2\ OperationalGas$$

This axiom states that the refrigeration system in the building cannot use more than two types of operational gas - this implies either CO2, Ammonia or both. Figure 8-3 and Figure 8-4 show these restrictions in the class view of Protégé:

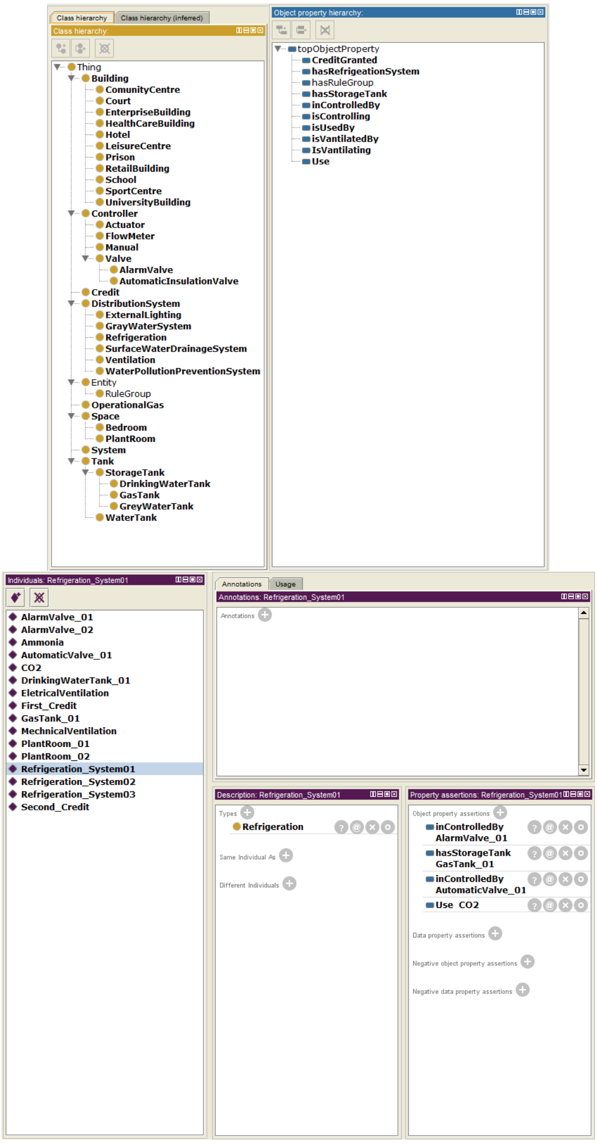

Figure 8-3 Classes, Object Properties and Instances of BREEAM-ONTO ontology

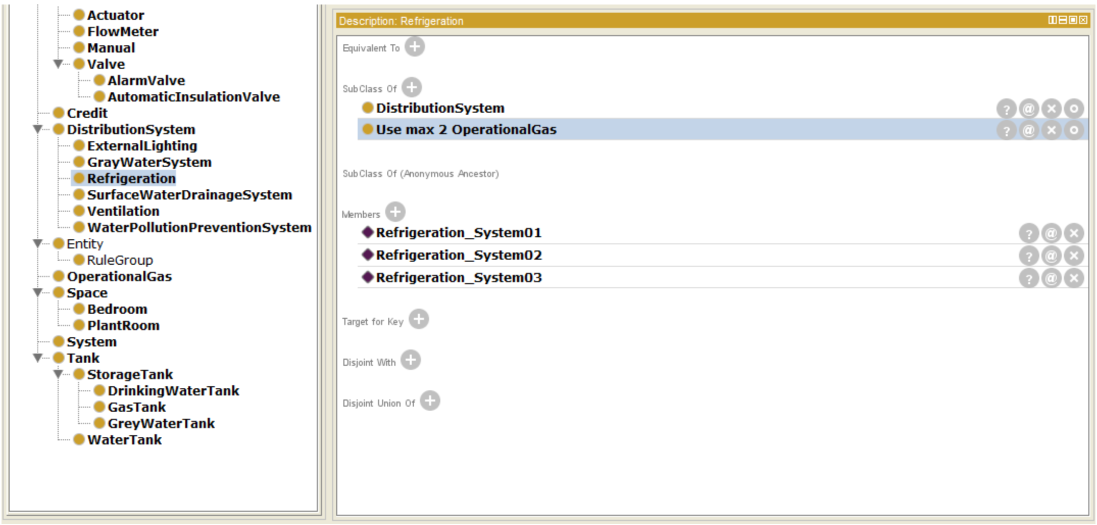

Figure 8-4 Object restriction to Class in BREEAM-ONTO ontology

By following the ontology development guide, all the objects and relationships can be mapped to Classes, Properties and individuals respectively in the BREEAM-ONTO ontology - this is shown in Figure 8-5. The lines marked by different colours demonstrate the relationships between classes.

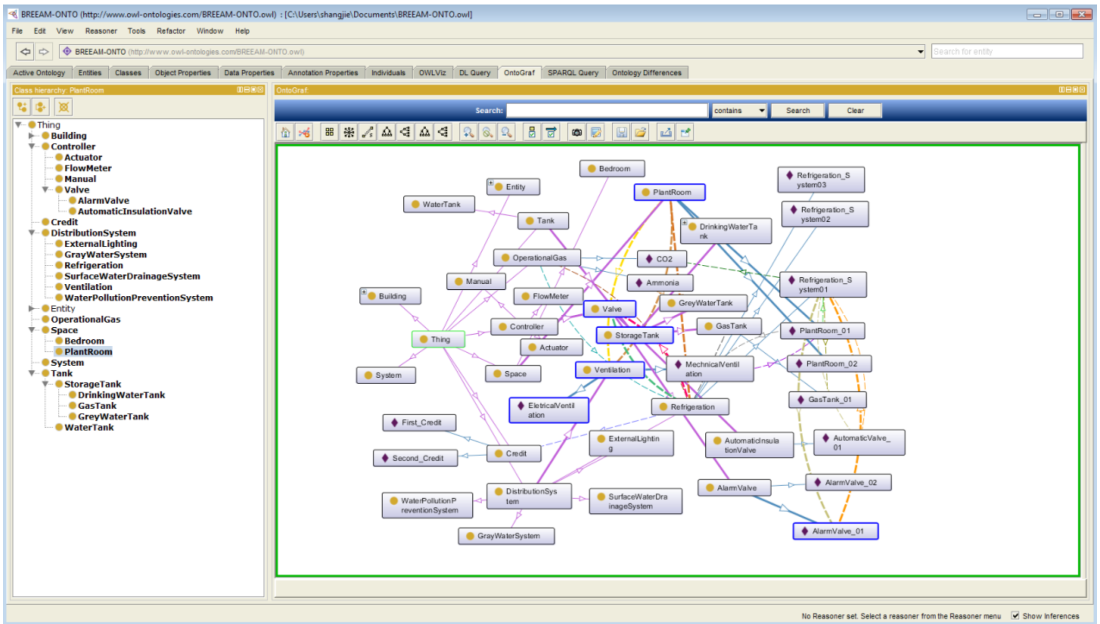

Figure 8-5 Multi-relationships between classes of BREEAM-ONTO ontology in Protégé 4.3

Based on the initial facts (Classes and Property restrictions) in the developed ontology, and the defined rules as illustrated in Table 8-3, BREEAM credits will be asserted as a new fact to the instances of refrigeration systems that comply with the requirements given in the assessment criteria. Figure 8-5 presents the output from ontology reasoning.

Table 8-3 The output of BREEAM-ONTO ontology reasoning

Credit 1
(Refrigeration_System01), (isVantilatedBy), (MechanicalVentilation) in (PlantRoom), and (isControlledBy), (AlarmValve_01) and (AutomaticIsulationValve_01) → First_credit.
Credit 2
(Refrigeration_System01), (Use), (CO2) as refrigerant → Second_credit.

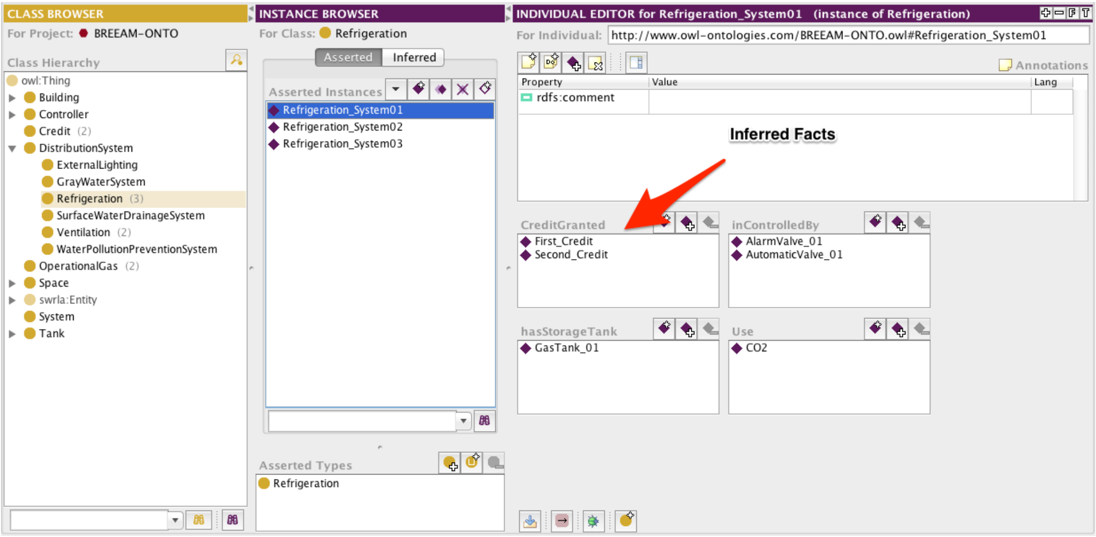

Figure 8-6 The output of BREEAM-ONTO ontology reasoning

8.5 Results and discussion

By adopting the ontological representation approach of the knowledge constructs relating the components of *'Refrigeration system'* in BREEAM, the semantically-applicable constructs were represented in the Protégé ontology editor. These include the top-level *Distribution system*, together with the lower-level concepts such as *refrigerants, controllers, locations* and *concepts*. The relationship between these concepts has been defined with the functional constrains to establish the initial knowledge model. The semantically-enriched knowledge model settled the basis to implement the initial prototype for an extensible ontology for sustainability compliance checking. The key of the exploration is the mapping between Ifcowl and the developed OWL, to determine whether the model is complied with the requirements for sustainability compliance checking.

8.6 Conclusion

In this chapter we have presented a way of using engineering ontology as a method of automatic sustainability compliance checking. We focussed on lifting a context data model into an ontological level to profit from methods in the emerging field of interoperability based on knowledge representation. We have applied our technique to BREEAM data and we investigated the potential of mapping the developed BREEAM OWL with IFC OWL as a starting point for the future use of ontology in the field. We have suggested how the ontology can be used to reduce complexity of processing information for automatic extraction of data. However, the use of Ontology for automatic compliance checking is on its early stages and its development is pertinent with the development of model views of IFC from one side and the development of ontological representation of data models correspondent with the requirements of the targeted regulations. Table 8.4 summarize a comparison results using different criteria.

Table 8-4 Comparison between three approaches of BREEAM assessment process

Criteria	Manual Assessment Process	Ontology Based assessment	Rules Based Assessment
Accuracy	Compliance checking accuracy depends on the accuracy of the gathered information and the experience of the assessor. This is subjected to human omissions.	The accuracy depends on the accuracy of classes' definitions and relationship identifications.	The accuracy depends on the accuracy of rules generation from the textual document
Consistency	Consistent results due to human common sense and logical sight	Depends on the consistency of BREEAM ontology and IFC OWL	High consistency due to the fact that the rules are generated from the regulation document directly.
Time of assessment	Time consuming due to huge amounts of data to be processed	Much faster. It only takes few minutes to conduct the assessment. However, time is needed for building BREEAM ontology and definition of competency questions according to regulation requirements..	The assessment only takes few minutes to conduct .However; time is needed for adding the missing data to the IFC data model.
Technical errors	Minimum technical issues due to minimum involvement of ICT systems.	Subjected to technical errors during data identifications and classification	Subjected to technical errors the conversion of textual documents into machine readable rules.
Efforts	Requires lots of efforts	Less effort is needed for the assessment. Professionals are only needed for the system development	Less effort is needed for the assessment. Professionals are only needed for the system development.
Cost	Very expensive process	Could be conducted repeatedly with no further investment	Could be conducted repeatedly with no further investment
Transparency	Lack of transparency due to the huge amounts of data which is dominated by the assigned BREEAM assessor	High transparency features of Ontology systems in terms of data sharing and re use	High transparency due to the evolvement of advanced information technologies and data sharing

Chapter 9

Model View Definitions (MVD) For Sustainability Compliance Requirements

This chapter describes the steps of developing a model view definition (MVD) to extract sub-sets of sustainability compliance checking data from the IFC data model using the NBIMS process.

9.1 Introduction

Although the IFC rich data-modelling schema is recognised as the common data exchange format in AEC-FM, IFC's richness also makes it highly-redundant. The IFC data model offers different definitions for objects, properties and relations; this divergence in data representation causes inconsistencies in assumptions made during the data exchange. Thus the exchange becomes unreliable and poses a considerable barrier to the advancement of BIM; a BIM's task stresses the inter-operability and smart exchange between parties involved within a workflow AEC (Weise et al.,

2003). The national BIM standard committee (NBIMS) perceived this major issue, and proposed the concept of MVD to facilitate the BIM data exchange. The ‘term model view definition’ (MVD) identifies virtual structured sub-sets of the IFC data model, complied dynamically from the IFC schema. These sub-sets precisely describe the exchange requirements between parties involved in a workflow of construction projects (Hietanen and Final, 2006).
During its life cycle, a construction project is characterised by a large number of activities run by different participants. Many of these actors need to develop the information at some point of the project, and hence need to share this information with other participants. Hence, the development of MVD for certain exchange requirements is heavily-constrained by the participants, the activity involved, and the type of data for each exchange. This context is summarised in Figure 9-1; the figure demonstrates the exchange scenario between well-defined roles for a specific purpose within a particular stage of a project’s life-cycle, (in this figure, the compliance checking process is illustrated). This can be abbreviated by what is known as a “use case”; basically, a process within the life-cycle of the project is a series of use cases composed of detailed process parts. Every use case has a set of information that is exchanged between the actors involved (A1, A2, etc.); these sets of information represent exchange models (EM). An exchange model comprises a list of exchange objects (EO) that encapsulate definitions of attributes (Att) for the exchange functional requirements. All of these details need to be identified as part of the MVD development (Gordijn et al., 2000).

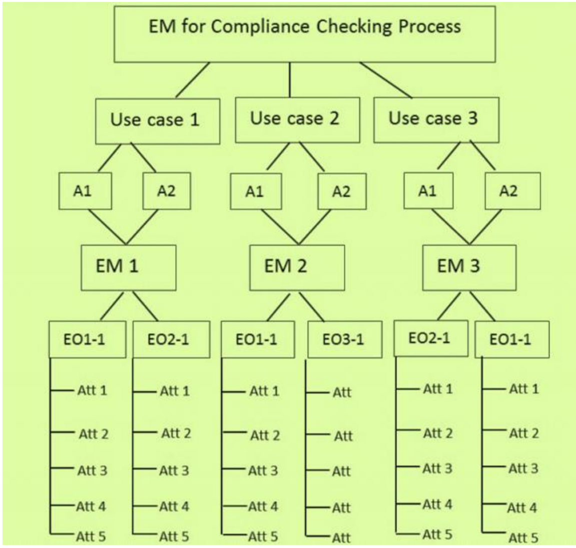

Figure 9-1 Exchange scenario for compliance checking process

There are a number of active industrial MVD development efforts for the major domains of AEC-FM summarised in IFC Solutions Factory (BuildingSMART, 2012). However, there is a clear gap in the market, in that there is no intention to develop an MVD for the domain of sustainability compliance checking. The most relevant effort is the ‘Nordic Energy Analysis (subset of CDB-2010)’; this MVD covers the exchange requirements for data, concerning the architectural design and energy analysis data in the concept design stage. According to energy analysis process, the exchange requirements for the Nordic Energy Analysis MVD include data about the building location, spaces and heat transfer surfaces, and information about the thermal properties of building elements which significantly affect the energy performance of the design. The current MVD could pave the way for developing a sustainability domain MVD, to be used directly for compliance checking. Such an MVD could be crucial for extracting sub-sets of information regarding sustainability compliance checking, and eventually to facilitate the automation of the process. One of the challenges facing this development is that a detailed coordinated workflow for the compliance checking process has not been precisely defined. The assessment procedure comprises different activities conducted by different parties; this includes energy efficiency performance measures, building element properties assessment and design aspects characteristics evaluation (Sadiq and Governatori, 2010).

9.2 Using the NBIMS process for MVD development

The National Building Information Modelling Standard (NBIMD) sets the generic guidelines for the development of a standard for information exchange during the workflow of a construction project. This exchange covers the flow of complete building information for all phases of design, construction and operation, coupled with the related disciplines. The development of MVD is derived from acquiring exchange requirements from the breadth of activities run by industry participants. These ERs are rationalised and formed into an Information Delivery Manual (IDM), before finally developing the MVD according to a defined IFC implementation. Ultimately, the successful development of an MVD should be driven by the requirements of a deployment in a particular phase of the design (Venugopal et al., 2011). Without the intention of a harness - a domain driven-MVD - there would be no reason for it to exist.

Similar to other phases during the workflow of a construction project, compliance checking is a major task in which a significant number of industry participants are involved. This task covers a wide range of information related to a diverse set of activities, including: architectural design, management issues, energy aspects, building elements properties and material specifications. The steps of developing an MVD for this particular task are graphically outlined in Figure 9-2. However, this development faces some significant challenges.

Sustainability compliance checking is currently conducted according the requirements of the involved parties. There is no well-defined standard for conducting this task. In the UK, most construction projects work-flow follow the RIBA plan of work; this is a plan outlining how the process of the construction project is organised (Hughes, 2003) - this plan was initiated by the royal institute of British Architects (RIBA). The plan is made up of seven stages, illustrated in Figure 9-3. Each stage is meant to guide the participant during the stage, and to ensure that all aspects of the construction phase are covered. Since the UK government has stressed the need for an efficient construction industry, which inherently enshrines the principles of sustainability, the RIBA has complied with this, and developed a new generation of the ‘RIBA Plan of Work’, which incorporates the principles of sustainable design, and provides the infrastructure for BIM involvement, aiming to contribute to the transformation in the construction sector (Sinclair, 2012). The involvement of the sustainability compliance checking aspect is an embedded process, along with the BIM implementation through the work-flow of a construction project, and is still in its early stages of development. There is still a need to precisely-identify the actors participating in this task, the activities involved and the breadth of information needed to formalise the ‘business process’, according the MVD development requirements.

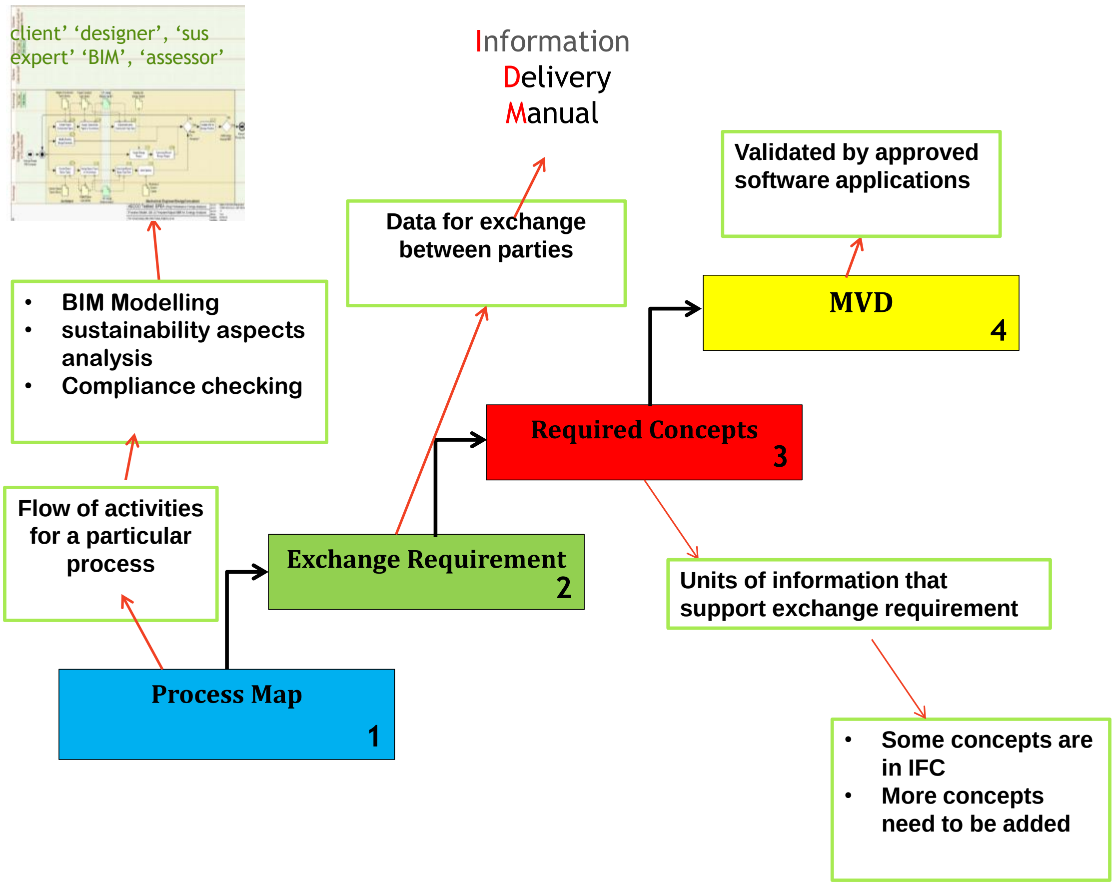

Figure 9-2 Steps for MVD development for sustainability compliance domain

As illustrated in Figure 9-2, the first stage of creating an Information Delivery Manual (IDM), and eventually developing an MVD for a particular domain, is 'process mapping'. A process map describes the flow of activities for a particular business process (William East et al., 2012), and it enables an understanding of the configuration of activities that make it work. The process map precisely clarifies the actors involved in a particular task, and the breadth of information required to be shared between the actors. In order to finalise the process map for a business process, a group of experts in the related domains needs to be formed, to address the different aspects of the process. This group is responsible for identifying the process stages, the actors involved in each stage, and the responsibilities of each actor. Furthermore, the panel defines the exchange models, and implements a strategy for data transactions between the actors within the stage of the process, or between different stages(Katranuschkov et al., 2010b).

	Preparation and Brief	Concept Design	Developed Design	Technical Design	Construction	Handover and Close Out	In use
Sustainability aspects	• Formal sustainability targets • Environmental requirements (building lifespan, future climate parameters) • consultations, survey or monitoring • Site Waste Management Plan	• sustainability pre-assessment • environmental impact of key materials • resilience to future changes in climate • Building Regulations Part L	• full formal sustainability assessment considered • carbon/energy declaration undertaken • design been reviewed • Building Regulations Part L	• formal sustainability assessment completed • Building Regulations Part L submitted • carbon/energy declaration been updated • non-technical user guide been drafted • the format and content of the Part L log book been agreed • sustainability criteria updated • agreed sustainability criteria demonstrated	• design stage sustainability assessment certified • sustainability procedures been developed • Handover Strategy Programme reviewed • Information for post construction sustainability certification issued	Assistance with the collation of post-completion information for final sustainability certification been provided	• Observation of the building operation in use and assistance with fine tuning and guidance for occupants undertaken • energy/carbon performance been declared
Participants	Architect, construction consultant, surveyor, geologist, coordinator, project manager	Sustainability assessor, materials expert, coordinator, project manager	Sustainability assessor, energy expert, construction consultant coordinator, project manager,	Sustainability assessor, energy expert, construction consultant, coordinator, project manager	Sustainability assessor, energy expert, construction consultant, coordinator, project manager	coordinator, project manager	coordinator, project manager
Information Domain	Architecture, sustainability criteria, weather data, site data	Architecture, Materials specifications, sustainability criteria, weather data, site data building elements properties, management data	Architecture, Materials specifications, sustainability criteria, weather data, site data building elements properties, managements data	Architecture, Materials specifications, sustainability criteria, weather data, site data building elements properties, managements data	Architecture, Materials specifications, sustainability criteria, weather data, site data building elements properties, managements data	Architecture, Materials specifications, sustainability criteria, weather data, site data building elements properties, managements data	Architecture, Materials specifications, sustainability criteria, weather data, site data building elements properties, managements data

Figure 9-3 Sustainability aspects over the RIBA plan of work

Once the process map is finalised, the next step is to define the detailed exchange requirements; these cover a set of information that needs to be exchanged to support a particular business requirement at a particular stage of a project. This stage provides a description of the information in non-technical terms, and leads to the formation of the information delivery manual (IDM) (Eastman et al., 2009a). An IDM is a standard for information representation for domains. There are number of IDMs agreed by professional bodies (Wix and Karlshoej, 2010), and published for exchange between parties. However, IDM cannot be exchanged formally between software applications, unless it has complied with a data representation schema.

The IFC data schema is currently used for MVD development (Hietanen and Final, 2006); IFCs are the machine-interpretable exchange mechanisms supporting the IFC interoperable applications. The third stage of MVD development - illustrated in Figure 9-2 - comprises the involvement of the IFC to define the data items, where the required concepts of information are defined as functional parts; these are compiled into the IFC data model, to support an exchange requirement. These functional parts are a complete schema in their own right, as well as being a sub-set of the full standard on which they are based.

The sub-schema is an aggregate of functional parts, constrained by rules within a particular process. Finally, the functional IDM specifications are mapped to the IFC schema, according to the rule-constrained IDM requirements. This stage requires comprehensive knowledge of the IFC data model schema and its logical structure (Kiviniemi, 2009, Panushev et al., 2010). It is challenging to develop an MVD for sustainability compliance checking, since the current versions of IFC lacks representation of the full breadth of sustainability data in the compliance checking domain (Bazjanac, 2008). Chapter 4 of this thesis shows the weaknesses of the IFC in detail - the area for IFC extension has been highlighted.

9.3 Conclusion

This chapter discusses the possibility of developing MVD for sustainability requirements. It is important to note that, even though compiling input data requirements for sustainability compliance checking is one of the objectives of the current research, the formation of an MVD for the sustainability compliance checking domain is not the primary scope of this thesis. However, a roadmap for MVD development is given in the following (NBIMS) outlines. A significant challenge facing MVD development for sustainability compliance checking is that the IFC lacks representation of the breadth of data needed for that process. Chapter 4 of this thesis shows the weaknesses of the IFC in detail, and the area for IFC extension has been highlighted.

Chapter 10

Summary, Conclusion Remarks and Future Work

10.0 Summary

The building design and construction process is conditioned by a sequence of obligations and regulations that buildings should comply with at different stages of the construction process. These regulations are continuously expanding in their requirements, in order to address growing environmental concerns, social considerations and economic factors. Building designs are becoming more sophisticated, within the competitive construction industry and cultural trends towards embedded information technology. The aim of this thesis is to improve and facilitate the sustainability compliance checking process, by focusing on inter-operability between existing methods and building information modelling. This is fulfilled by achieving the objectives stated in Chapter 1, and by addressing the research questions.

This chapter starts with a summary of the research steps taken to fulfil the research objectives (Section 10.1). Concluding remarks are then presented (Section 10.2), and future work is proposed (Section 10.3). The thesis continues with Chapter 2, which gives details of environmental assessment methods and rating systems in the construction industry, and also outlines different approaches, frameworks and methodologies for environmental assessment, with a focus on the BREEAM assessment method.

Environmental performance standards and regulations are also described in this chapter, and various tools for sustainability performance analysis are also discussed. Overall, the BREEAM standard is identified as being able to be supported by building information modeling, to facilitate the compliance checking process. Methods for assessing a building's sustainability are also presented in Chapter 2; these methods are underpinned by human efforts in conducting compliance checking, and have offer high reliability, but are associated with significant efforts and costs.

Chapter 3 presents a review of the process of information management in the construction industry. In addition, the barriers and limitations, collaboration and interoperability issues of BIM adoption are discussed. This chapter focuses on the information context presented by BIM, and discusses the IFC schema used to identify a connection between BIM data and the information needed for compliance checking. The fundamentals and features of previous efforts of automated compliance checking are discussed in this chapter, to underpin the design of the research methodology applied.

Chapter 4 discusses different research approaches, and introduces the research methodology; it reveals the originality of the approach employed, and describes the research design used to answer the research question. Chapter 5 describes the methodology of converting sustainability regulations into executable rules, which can be executed by the rules engine. This chapter gives a detailed explanation of how rules are extracted using decision logic RASE methodology. This process has created formalized business rules, and a taxonomy of the domain of compliance requirements. This taxonomy describes all objects and attributes that are needed for the assessment. Based on that taxonomy, a list of data items is identified, and a dictionary of compliance data requirements is generated, which results in a set of data to perform an enhancement to the current IFC standards

RASE mark-up language is used to provide a robust foundation for the automated model checking system; the methodology is applied to BREEAM, and it is applicable to any domain of regulations with a similar context. It is concluded that the difficulty of the rules generation depends on the complexity of the original regulatory statements. The conversion of regulatory textual formats into an executable automated rules system represents the key step to facilitate the mapping of compliance requirements to a building information model and to automate the compliance checking - this is outlined in Chapter 6.

In Chapter 6, the process of integrating the developed system into a BIM environment is described. The semantic expansion of IFC to address BREEAM requirements is explained in detail. The details of how the rule engine executes and processes the pre-defined rules for compliance requirements are also evidenced, since the rules-based approach for automating sustainability compliance checking has some limitations when compliance requirements are implicit within the IFC database.

The automated sustainability compliance checking system is validated in Chapter 7 using two case studies: The Monument Pilot Project and The Orthopaedic Hospital Building. The developed system is used to process the IFC data to check compliance with the pre-defined rules stored in the system. The developed system correctly calculates the results, as judged by a comparison with the traditional BREEAM assessment method. The approach shows valid results which could significantly contribute to automating compliance checking. Nevertheless, significant areas of frustration have been reported, and further efforts are needed before a fully-automated compliance checking system can be achieved; this is especially true where it is difficult to implement logical coded rules in representing some implicit compliance requirements stated within the regulations. Challenges and drawbacks are justified while the advantages of the system implementation are reported. The chapter also investigates the usability of the system, and describes the efficiency savings deemed possible by its implementation.

In Chapter 8, BIM Level Three, and the use of engineering ontology to extract data from IFC for automated compliance checking is explored. It is concluded that the use of ontology and the semantic web offers a formal way to represent implicit human knowledge in an explicit presentation, based on logic theory. This chapter focuses on elevating a context data model to the ontological level, in order to benefit from methods in the emerging field of inter-operability based on knowledge representation. The approach is applied to BREEAM data, and an ontological taxonomy of BREEAM data is developed. In this chapter, the potential for mapping the developed BREEAM OWL with IFC OWL is investigated as a starting point for the future use of ontology in the field.

Finally, Chapter 9 investigates the potential for developing an MVD as a sub-set from IFC data model for sustainability compliance checking requirements in general, and more specifically for BREEAM data sets

10.1 Conclusion Remarks

- The incorporation of advanced technologies and the principles of information sharing have limited practical application in the current regulatory compliance checking processes implemented in construction sector. Therefore, it is crucial to address the complexity of regulatory compliance checking, and to harness the currently-evolving technologies and the principles of interoperability and information sharing, to develop more efficient regulatory compliance checking processes.
- The information required to support the environmental assessment process and compliance checking is currently fragmented across domains, and is not ready to be used as guidance to a designer, or to be accessible within a software-based design environment. In addition, the regulations and standards have not been designed in a manner that allows the incorporation of information technologies for automated processes - the current textual format requires human interpretation and judgment.
- Using the virtual environment and the features of building information modelling to check building compliance against targeted regulations is an efficient solution which promotes sustainable design and construction, however, extracting the required data from the BIM model is challenging. The commonly-used data format for building models is IFC; the IFC data model has been described as a rich data

model, but it lacks representation of data requirements for certain domains, and the requirements for environmental sustainability compliance checking are fragmented within the data repository.

- Using a rules-based system to extract regulatory compliance requirements is efficient. However, the rules engine can only capture the explicit data requirement from the IFC file, and it is difficult to deal with the implicit concepts and to track and evaluate attributes of objects whose instances are themselves classes defined in IFC.
- Elevating a context data model to an ontological level enables it to benefit from methods in the emerging field of inter-operability based on knowledge representation. The technique developed in this thesis is applied to BREEAM data, and the potential of mapping the developed BREEAM OWL with IFC OWL is investigated, as a starting point for the future use of ontology in the field. It is suggested how the ontology can be used to reduce complexity of processing information for the automatic extraction of data. However, the use of ontology for automatic compliance checking is in its formative stages, and its development is pertinent to the development of model views of IFC, and with the development of the ontological representation of data models correspondent with the requirements of the targeted regulations.
- Developing an MVD for a certain domain can facilitate the extraction of a sub-set of data from IFC.
- By undertaking the case studies described in this thesis, the process is been validated through construction sustainability domain experts utilising the methodology, and supporting software to (a) specify the regulations without the need for significant software development, and (b) maintain and update the regulations as the standards within the industry change. This process of updating regulations is carried out by simply updating the metadata and dictionary mappings that were developed when the system was specified.

10.2 Future work

In the future, it is anticipated that the natural language processing, narrative analysis, rules processing and automatic ontology alignment efforts will result in the semi-automation of various stages within the proposed methodology. This is especially true for the mappings between the semantics of regulations, the data format semantics, and the semi-automatic extraction of key regulations from within textual documents. It is also envisaged that the semantic resources developed through the use of the proposed methodology will be valuable to industry; this may especially facilitate various efforts in the standardisation of semantics within domains, where multiple regulation ontologies can be analysed together with the core domain ontology, to ascertain and explore the semantic differences that have naturally arisen even within the same domain.

Finally, it is the author's vision that, as the importance of having computable regulations grows, and the quantity and complexity of data stored electronically within domains also grows, that regulations should be specified in a structured and semantically-rich way, where the logical relationships between items is explicitly specified. This complete paradigm shift in the way that regulations are written means that, from the very start of the design of the regulations, they are designed to be automated, and the human-readable documentation is treated as an output of the automated regulations, rather than as an input to create automated compliance checking.

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Appendices

Appendix A complete list of data-BREEAM

Table 11-1 User input data/ potential extension to IFC

Topic	Property	IFC Type	Issues Appearing In
Access Statement	addresses access to and through development for all users	boolean	MAN04
Access Statement	allow for public access to shared facilities without giving uncontrolled access to other parts of building	boolean	MAN04
Aftercare Commitment	include on site fm training including walkabout	boolean	MAN01
Aftercare Commitment	include provision for longer term after care	boolean	MAN01
Aftercare Commitment	includes meeting to introduce after care team	boolean	MAN01
Aftercare Commitment	includes meeting to introduce building user guide	boolean	MAN01
Aftercare Commitment	includes meeting to present key information and take questions	boolean	MAN01
Aftercare Commitment	provision for initial aftercare include onsite attendance for 4 weeks after handover	boolean	MAN01
Appliance	identified as product with green tick on buying solutions	boolean	ENE08
Appliance	is in energy star labeling scheme	boolean	ENE08
Appliance	is in enhanced capital allowance scheme	boolean	ENE08
Appliance	meets government buying standards	boolean	ENE08
Appliance	rating	enum	ENE08
Appliance	recommended by energy saving trust website	boolean	ENE08
Appliance	type	enum[]	ENE08
Boiler System	end user energy consuming use is identifiable through labelling or data output	boolean	ENE02
Boiler System	lead boiler sub metered	boolean	ENE02
Boiler System	modular	boolean	ENE02
Boiler System	overall power rated input	double	ENE02
Boiler System	power of each boiler in system	double	ENE02
Building	access to building direct from public highway	boolean	HHEA06
Building	air intake distance from source of external pollution	enum[]	HEA02
Building	all decorative paints and varnishes comply with bsen13300	boolean	HEA02
Building	alo recommendations covered	boolean	HEA06
Building	amenities within 1000m	enum[]	TRA02
Building	amenities within 500m	enum[]	TRA02
Building	appropriate for connection to chp	boolean	ENE04
Building	areas identified where vehicular trolley and pedestrian movement occurs	boolean	MAT05

Topic	Property	IFC Type	Issues Appearing In
Building	areas with separate zoning	enum[]	HEA01
Building	building elements assessed for mat01 points	enum[]	MAT01
Building	building likely to result in large packaging or compostable waste streams	boolean	WST03,WST03
Building	building user are living out personnel	boolean	TRA04
Building	bus service provided at beginning and end of working day	boolean	TRA01
Building	communal laundry has specification of heat recover from waste water	boolean	ENE08
Building	communal laundry uses greywater for part of washing process	boolean	ENE08
Building	community building	boolean	TRA05
Building	complementary to hse acop	boolean	HEA04
Building	compliant wheelchair or buggy storage spaces	int	TRA01
Building	complies with hea2 criteria 17 and 18	boolean	ENE07
Building	complies with light pollution criteria in guidance notes	boolean	POL04
Building	components included in wat01 calculation	enum[]	WAT01
Building	contains only products with no formaldehyde containing materials	boolean	HEA02
Building	has travel plan developed considering all types of relevant travel	boolean	TRA05
Building	has travel plan developed considering all types of users	boolean	TRA05
Building	heat load of equivalent building regulation compliant building	double	POL02
Building	heating cooling occupant control decisions based on	enum[]	HEA03
Building	heating cooling strategy	enum[]	HEA03
Building	in prison establishment	boolean	TRA03
Building	indoor air quality plan considers	enum[]	HEA02
Building	installation of durability measures will form part of future fit out and installation	boolean	MAT05
Building	is heating cooling hot water system used for cfsh compliance same specification that those for other areas	boolean	POL02
Building	is part of site that already has compliant breeam travel plan relevant to new users of the building	boolean	TRA05
Building	lifecycle green house gas emissions reported on basis of 60 year building life	boolean	MAT01
Building	lifting platforms stairlifts are only for aiding persons with impaired mobility	boolean	ENE06
Building	local low zero carbon energy technology installed inline with feasibility study recommendations	boolean	ENE04
Building	local low zero carbon technologies regulation co2 emissions percentage reduction	double	ENE04
Building	major process water users are sub metered	boolean	WAT02
Building	majority of installed fume cupboards are recirculatory filtered	boolean	ENE07
Building	maximum and minimum temperatures for summer and winter reported with tor metric	boolean	HEA03
Building	measures implemented	enum[]	TRA05
Building	measures installed to attenuate noise to a level where in compliance	boolean	POL05
Building	measures taken to reduce formaldehyde concentration over 30 minutes to	double	HEA02
Building	measures taken to reduce tvoc concentration over 8 hours to	double	HEA02
Building	modelling demonstrated that building design and services strategy can deliver thermal comfort in accordance with building bulletin 101	boolean	HEA03
Building	modelling demonstrated that building design and services strategy can deliver thermal comfort in accordance with cibse guide a	boolean	HEA03
Building	modelling demonstrated that building design and services strategy can deliver thermal comfort in accordance with htm 0301	boolean	HEA03
Building	number of building residents	int	TRA01
Building	number of classes per year group	int	TRA03
Building	number of consulting examination treatment therapy room or ae cubicle	int	TRA04
Building	number of consulting rooms	int	TRA03
Building	number of medical staff	int	TRA04
Building	number of public users of building	int	TRA01
Building	number of recycling containers	boolean	WST03
Building	number of staff in building	int	TRA01
Building	number of visitors expected	int	TRA01
Building	occupant has confirmed specified floor and ceiling finishes	boolean	WST04
Building	occupants affected by complex building services	boolean	MAN01
Building	on an mod site	boolean	TRA01
Building	operates according to fixed shift pattern	boolean	TRA01
Building	organic waste stored or composted	boolean	WST03

Topic	Property	IFC Type	Issues Appearing In
Building	percentage baseline water consumption improvement	double	WAT01,WAT01,WAT01,WAT01,WAT01
Building	products compliant with bs13964	enum[]	HEA02
Building	products compliant with bs13986	enum[]	HEA02
Building	products compliant with bs13999	enum[]	HEA02
Building	products compliant with bs14041	enum[]	HEA02
Building	products compliant with bs14080	enum[]	HEA02
Building	products compliant with bs14342	enum[]	HEA02
Building	products compliant with bs233	enum[]	HEA02
Building	products compliant with bs234	enum[]	HEA02
Building	products compliant with bs259	enum[]	HEA02
Building	products compliant with bs266	enum[]	HEA02
Building	products compliant with bs3046	enum[]	HEA02
Building	recyclable storage located in a dedicated non obstructive position	boolean	WST03
Building	recyclable storage located in a dedicated non obstructive position in a communal kitchen	boolean	WST03
Building	requires humidification	boolean	HEA04
Building	scheme used in csh assessment is included in list of breeam compliant schemes	boolean	MAN02
Building	shell only	boolean	POL01,POL02,POL04,POL05
Building	sub metering specified to allow for monitoring of functional areas	boolean	ENE02
Building	subjects taught up to and including a-level	boolean	ENE07
Building	tor confirmed acceptable	boolean	HEA03
Building	tor metric available in cibse guide a	boolean	HEA03
Building	tor metric complies with building bulleting 101	boolean	HEA03
Building	tor metric reported via breeam scoring tool	boolean	HEA03
Building	total number of building occupants	int	TRA01
Building	transport system energy consumption estimated	enum[]	ENE06
Building	transportation demand has been analysed to determine optimum size of lifts moving walks or escalators	boolean	ENE06
Building	tvoc concentration measured post construction over 8 hours	int	HEA02
Building	type	enum[]	POL02,POL02,POL02
Building	ventilation meets requirements of building bulletin 101	boolean	HEA02
Building	ventilation meets requirements of htm0301	boolean	HEA02
Building	ventilation systems designed in compliance with best practice in acdp 20001	boolean	HEA02
Building	volume of non hazardous construction waste generated	double	WST01,WST01,WST01
Building	water outlet provided for waste composting storage facility	boolean	WST03
Building	water systems compliance with health and safety legionnaires measures	boolean	HEA04
Building	water systems in compliant with measures outlined in html 04-01	boolean	HEA04
Building Travel Plan	based on existing travel plan	boolean	TRA05
Building Travel Plan	confirmed will be handed over to tenant	boolean	TRA05
Building Travel Plan	considers measures tailored to minimize impact of operational transport	boolean	TRA05
Building Travel Plan	contents of site specific survey	enum[]	TRA05
Building Travel Plan	measures implemented	enum[]	TRA05
Building Travel Plan	occupier confirms travel plan will be implemented	boolean	TRA05
Building Travel Plan	owner confirms will be support by building management	boolean	TRA05
Building User Guide	allows building and site related information to be available to all future users	boolean	MAN04
Building User Guide	contains	enum[]	MAN04
Building User Guide	designed to be appropriate to all building users	boolean	MAN04

Topic	Property	IFC Type	Issues Appearing In
Composting Space	has vehicular access and manoeuvring space	boolean	WST03
Contamination Site Investigation	conducted by a specialist	boolean	LE01
Contamination Site Investigation	contaminant sources identified	boolean	LE01
Contamination Site Investigation	degree of contamination identified	boolean	LE01
Contamination Site Investigation	included a risk assessment and appraisal	boolean	LE01
Contamination Site Investigation	options for remedying sources of pollution identified	boolean	LE01
Contamination Site Investigation	remidation required consists of removal of asbestos from buildings on site	boolean	LE01
Contractor	accounts for commissioning program responsibility and criteria within programme of works	boolean	MAN01
Contractor	ccs score	double	MAN02,MAN02
Contractor	operates an ems	boolean	MAN03,MAN03
Contractor	role	enum	MAN01,MAN01,MAN02,MAN02,MAN02,MAN03,MAN03
Contractor	thermographic survey accounted in budget and programme of works	boolean	MAN01
Contractor	uses compliant construction scheme	boolean	MAN02
Design Consultation	all feedback summarised within approved design intent document	boolean	MAN04
Design Consultation	consultation contains	enum[]	MAN04
Design Consultation	consultation feedback used for monitoring and quality control of building throughout design and procurement	boolean	MAN04
Design Consultation	consultation plan includes defining methods of consultation for all parties	boolean	MAN04
Design Consultation	consultation plan includes details of how parties will be kept informed	boolean	MAN04
Design Consultation	consultation plan includes timescale	boolean	MAN04
Design Consultation	consultation plan prepared	boolean	MAN04
Design Consultation	consultation process carried out by third party at brief and design stages	boolean	MAN04
Design Consultation	consultation process utilised a compliant method	boolean	MAN04
Design Consultation	design intent document has been approved by each of the main parties/stakeholders	boolean	MAN04
Design Consultation	feedback given on	enum[]	MAN04,MAN04
Design Consultation	feedback recieved by all relevant parties	boolean	MAN04
Design Consultation	findings of the consultation influences the design held before key and final design decisions are made	boolean	MAN04
Design Consultation	future actions	enum[]	MAN04
Design Consultation	parties consulted as part of consultation	enum[]	MAN04
Design Consultation	project team ensure that areas or features of historic or heritage value are protected	boolean	MAN04
Development Site	able to determine site species numbers	boolean	LE04
Development Site	additional predicted volume of run off must be prevented from leaving the site	boolean	POL03
Development Site	age of oldest tree	int	LE02
Development Site	aggregates obtained from waste processing site	boolean	WST02
Development Site	aggregates obtained on site	boolean	WST02
Development Site	aggregates sourced from waste from construction demolition and excavation	boolean	WST02

Topic	Property	IFC Type	Issues Appearing In
Development Site	amount of recycled or secondary aggregate	int	WST02
Development Site	appropriate consultant appointed to confirm compliance with breeam criteria	boolean	POL03
Development Site	can utilise compost	boolean	WST03
Development Site	categories for waste sorting	enum[]	WST01
Development Site	change in ecological value	double	LE03
Development Site	cleared prior to purchase	boolean	LE02
Development Site	construction works commenced prior to ecological survey	boolean	LE04
Development Site	consultant can justify why run off volume targets cannot be achieved	boolean	POL03
Development Site	consultant confirms no discharge for rainfaill up to 5mm	boolean	POL03
Development Site	contains broad leaved woodland habitat	boolean	LE02
Development Site	contamination remediated	boolean	LE01
Development Site	cycle lanes connect to any offsite cycle paths	boolean	HEA06
Development Site	cycle lanes provide direct access from entrance to cycle storage facilities	boolean	HEA06
Development Site	dedicated cycle lanes construction in accordance with local transport note	boolean	HEA06
Development Site	dedicated cycle lanes construction in accordance with nation cycle network guidelines	boolean	HEA06
Development Site	deemed to be significantly contaminated	boolean	LE01
Development Site	delivery areas accessed through general parking areas	boolean	HEA06
Development Site	delivery areas cross share pedestrian or cycle routes	boolean	HEA06
Development Site	delivery areas shared with other outside amenity areas	boolean	HEA06
Development Site	development permitted	boolean	POL03
Development Site	distance to aggregate source site	double	WST02
Development Site	distance to closest conservation protection or ramsar site	int	LE02
Development Site	distance to closest ssi	double	LE02
Development Site	drainage measures specified to ensure peak rate of run off is no greater than prior to development	boolean	POL03
Development Site	drop off areas are off or adjoining to access road	boolean	HEA06
Development Site	drop off areas provide direct access to pedestrian footpaths	boolean	HEA06
Development Site	drop off areas provided	boolean	HEA06
Development Site	ecological protection constructed by principal contractor	boolean	LE02
Development Site	ecological survey conducted	boolean	LE04
Development Site	ecological value	enum	LE02
Development Site	existing buildings on site contain	enum[]	LE02
Development Site	existing buildings will be demolished	boolean	WST01
Development Site	external water collection facilities provide sufficient volume for all buildings	boolean	WAT04
Development Site	features of ecological value only exempted from protection if ecologist confirms they are of little or no value	boolean	LE02
Development Site	features of ecological value removed	boolean	LE03
Development Site	features of ecological value removed as part of site clearance	boolean	LE02
Development Site	flood zone probability of flooding	enum	POL03,POL03
Development Site	flora fauna exists	boolean	LE05
Development Site	flower rich meadow grassland habitat present	boolean	LE02
Development Site	footpaths provide direct access from site entrance to building entrance	boolean	HEA06
Development Site	has a separate parking area for good vehicles away from manoeuvering area and car parking	boolean	HEA06
Development Site	has areas external to assessed building	boolean	HEA06
Development Site	has contaminated areas decontaminated solely for health and safety reasons	boolean	LE01
Development Site	has covered parking facility	boolean	HEA06
Development Site	has dedicated space for storage of skips and palettes away from car parking and manoeuvering areas	boolean	HEA06
Development Site	has ecological value	boolean	LE05
Development Site	has existing bms managed by the same occupier/owner	boolean	WAT02
Development Site	has high risk of contamination or spillage of petrol or oil	boolean	POL03
Development Site	has run off drains in areas with low risk of source watercourse pollution	boolean	POL03
Development Site	heathland habitat present	boolean	LE02
Development Site	hedges and natural areas protected by barriers	boolean	LE02
Development Site	hedges and natural areas protected by prohibiation of construction in their vicinity	boolean	LE02

Topic	Property	IFC Type	Issues Appearing In
Development Site	height above flood level of ground levels of topography or infrastructure adjacent to site	double	POL03
Development Site	increase in plant species calculated using breeam calculator using actual plant species data	boolean	LE04
Development Site	is split into smaller plots	boolean	LE01
Development Site	large development with high numbers of public users	boolean	HEA06
Development Site	lighting of cycle lanes in compliance with bs5489-1	boolean	HEA06
Development Site	lighting of footpaths in compliance with bs5489-1	boolean	HEA06
Development Site	lighting of pedestrian areas in compliance with bs5489-1	boolean	HEA06
Development Site	mature hedgerow present	boolean	LE02
Development Site	new locally appropriate ecologically valuable habitat created	boolean	LE05
Development Site	no practical solutions available for access to site above current level	boolean	POL03
Development Site	parking and turning areas designed for simple manoeuvering according to vehicle type	boolean	HEA06
Development Site	parking areas covered by alo recommendations	boolean	HEA06
Development Site	peak rate run off calculations include considerations for climate change	boolean	POL03
Development Site	pedestrian cross of vehicle access provided	boolean	HEA06
Development Site	pedestrian pathways signposted to other local amenities	boolean	HEA06
Development Site	percentage amount of base binder and surfaces from recycled aggregate	double	WST02
Development Site	percentage amount of building foundations from recycled aggregate	double	WST02
Development Site	percentage amount of concrete road surface from recycled aggregate	double	WST02
Development Site	percentage amount of floor slabs from recycled aggregate	double	WST02
Development Site	percentage amount of granular fill and capping from recycled aggregate	double	WST02
Development Site	percentage amount of gravel landscaping from recycled aggregate	double	WST02
Development Site	percentage amount of pipe bedding from recycled aggregate	double	WST02
Development Site	percentage amount of structural frame elements from recycled aggregate	double	WST02
Development Site	percentage of footprint on land previously developed	double	LE01
Development Site	percentage of hard landscaping achieving A or higher rating	double	MAT02
Development Site	percentage weight of non hazardous construction and demolition waste diverted from landfil	double	WST01,WST01
Development Site	post development lifetime run off volume no greater than prior to sites development	boolean	POL03
Development Site	post development peak run off rate reduced to a limiting discharge	boolean	POL03
Development Site	predicted run off volume calculations made with consideration for climate change	boolean	POL03
Development Site	previously developed	boolean	LE01
Development Site	resistant to flooding from artificial water sources	boolean	POL03
Development Site	resistant to fluvial flooding	boolean	POL03
Development Site	resistant to groundwater flooding	boolean	POL03
Development Site	resistant to sewer flooding	boolean	POL03
Development Site	resistant to surface water flooding	boolean	POL03
Development Site	resistant to tidal flooding	boolean	POL03
Development Site	roads raised to pavement level at pedestrian crossings	boolean	HEA06
Development Site	secondary aggregates obtained from non construction post consumer source	boolean	WST02
Development Site	secondary aggregates obtained from post industrial by product source	boolean	WST02
Development Site	situated within functional floodplain	boolean	POL03
Development Site	trees of significant ecological value protected by barriers	boolean	LE02
Development Site	trees over 100mm trunk diameter protected by barriers	boolean	LE02
Development Site	trees protected from direct impact	boolean	LE02
Development Site	trees protected from root asphyxiation	boolean	LE02
Development Site	trees protected from root severance	boolean	LE02
Development Site	type	enum	POL03
Development Site	undeveloped	boolean	LE01
Development Site	use	enum	WAT02
Development Site	using land within security perimeter fence on existing prison site	boolean	LE01
Development Site	volume of non hazardous construction waste generated	double	WST01
Development Site	vulnerable to flooding if drainage system fails	boolean	POL03
Development Site	watercourses present	boolean	LE02
Development Site	watercourses protection by cut-off ditches and site drainage	boolean	LE02
Development Site	wetland areas protected by cut off ditches and site drainage	boolean	LE02
Development Site	wetlands present	boolean	LE02

Topic	Property	IFC Type	Issues Appearing In
Development Site	years before assessment site cleared	int	LE02
Development Site	years since clearance	int	LE03
Dwelling	drying line provided for each bedroom over total of 30	double	ENE09
Dwelling	has adequate drying space with with posts and footings	boolean	ENE09
Dwelling	heating systems are cfsh compliant	boolean	POL02
Dwelling	length of drying line available	double	ENE09
Ecology Report	based on ecological survey	boolean	LE04
Ecology Report	confirmation held that recommendations will be implemented	boolean	LE04
Ecology Report	produced by suitably qualified ecologist	boolean	LE04
Ecology Report	provides recommendations for protection and enhancements of site	boolean	LE04
Ecology Report	recommendations implemented	boolean	LE04
Ecology Report	species increase confirmed by ecologist	int	LE04
Environmental Management System	implements best practice pollution prevention	boolean	MAN03
Environmental Management System	in compliance with bs8555	boolean	MAN03
Environmental Management System	phase audits 1 to 4 completed	boolean	MAN03
Environmental Management System	reached stage 4 of bs8555 implementation stage	boolean	MAN03
Environmental Management System	third party certified	boolean	MAN03
Escalator	fitted with passenger sensor to operate in stand by when no passenger demand	boolean	ENE06
External Lighting	automatically turned off between 2300 and 0700	boolean	POL04
External Lighting	colour rendering index	double	ENE03
External Lighting	controlled through time switch or daylight sensor	boolean	ENE03
External Lighting	evidence provided that specified to comply with specific security standards	boolean	POL04
External Lighting	is led luminaire	boolean	ENE03
External Lighting	luminous efficacy	int	ENE03
External Lighting	measured in lamp lumens per circuit	boolean	ENE03
External Lighting	type	enum	POL04,POL04
External Lighting	used between 2300 and 0700	boolean	POL04
Facilities Management Contract	intervals at which actions are taken	enum	MAN01
Facilities Management Contract	length of contract	int	MAN01
Facilities Management Contract	responsibilities of facility manager	enum[]	MAN01
Facilities Management Contract	stipulates annual building energy data given to bre global	boolean	MAN01
Facilities Management Contract	stipulates annual occupant satisfaction data given to bre global	boolean	MAN01
Facilities Management Contract	stipulates annual water consumption data given to bre global	boolean	MAN01
Facilities Management Contract	stipulates data used to check building performance and make necessary adjustments	boolean	MAN01

Topic	Property	IFC Type	Issues Appearing In
Facilities Management Contract	stipulates energy consumption data collection	boolean	MAN01
Facilities Management Contract	stipulates occupant satisfaction data collection	boolean	MAN01
Facilities Management Contract	stipulates progress will be monitored against water energy targets	boolean	MAN01
Facilities Management Contract	stipulates targets for energy usage	boolean	MAN01
Facilities Management Contract	stipulates that lessons learnt will be fedback to design team	boolean	MAN01
Facilities Management Contract	stipulates water consumption data collection	boolean	MAN01
Fume Cupboard	average design air flow rate per linear metre of sash opening	double	ENE07
Fume Cupboard	face velocity	double	ENE07
Fume Cupboard	manufactured in accordance with bs 14175	boolean	HEA02
Fume Cupboard	manufactured in accordance with building bulletin 88	boolean	HEA02
Fume Cupboard	recommendations in bs7989 met	boolean	ENE07
Fume Cupboard	recommendations in bsen14175 met	boolean	ENE07
Fume Cupboard	reduction in air flow does not compromise health and safety of bulding occupants	boolean	ENE07
Fume Cupboard	type	enum	ENE07
Greywater System	specified and installed in compliance with bs85525	boolean	WAT01
Greywater System	yield used to offset potable water demands	boolean	WAT01
Illuminated Advertisements	designed in compliance with ile technical report 5	boolean	POL04
Irrigation System	is a sub surface drip feed system	boolean	WAT04
Irrigation System	not required as planting is restricted to species that thrive in hot and dry conditions	boolean	WAT04
Irrigation System	reliant solely on precipitation	boolean	WAT04
Irrigation System	uses reclaimed water with appropriate sized storage system	boolean	WAT04
Irrigation System	utilises manual watering by landlord or occupier	boolean	WAT04
Irrigation System	zoned drip feed subsurface system with soil moisture sensors	boolean	WAT04
Kitchen	has home composting information leaflet	boolean	WST03
Laboratory Area	components having 2 percent reduction in energy consumption	enum[]	ENE07
Laboratory Area	containment area extract with hepa filtration fan power	double	ENE07
Laboratory Area	containment area extract without hepa filtration fan power	double	ENE07
Laboratory Area	containment level	int	HEA02
Laboratory Area	ducted laboratory local extract ventilation fan power	double	ENE07
Laboratory Area	filters are easily accessible for maintenance staff technicians for maintenance staff and technicians	boolean	HEA02
Laboratory Area	fume cupboard extract fan power	double	ENE07
Laboratory Area	general laboratory extract system fan power	double	ENE07
Laboratory Area	general laboratory supply air ahus with heating and cooling fan power	double	ENE07
Laboratory Area	measurement of volume flow rates of exhaust ducts take account of restrictions in fume cupboard leakage	boolean	ENE07
Lifecycle Cost Analysis	based on concept design proposals	boolean	MAN05
Lifecycle Cost Analysis	based on design development proposals	boolean	MAN05
Lifecycle Cost Analysis	components analysed	enum[]	MAN05

Topic	Property	IFC Type	Issues Appearing In
Lifecycle Cost Analysis	conducted in accordance with pd156865	boolean	MAN05
Lifecycle Cost Analysis	considers	enum[]	MAN05
Lifecycle Cost Analysis	demonstrated building components analysed at strategic and system level	boolean	MAN05
Lifecycle Cost Analysis	demonstrated building envelope analysed at strategic and system level	boolean	MAN05,MAN05
Lifecycle Cost Analysis	maintenance strategy considers	enum[]	MAN05
Lifecycle Cost Analysis	maintenance strategy developed based on lcc	boolean	MAN05
Lifecycle Cost Analysis	options selected allow dismantling and recycling of building components	boolean	MAN05
Lifecycle Cost Analysis	options selected give lower building energy consumption	boolean	MAN05
Lifecycle Cost Analysis	options selected give reduction in maintenance requirement	boolean	MAN05
Lifecycle Cost Analysis	options selected of critical value	boolean	MAN05
Lifecycle Cost Analysis	options selected require less replacement	boolean	MAN05
Lifecycle Cost Analysis	results implemented in design	boolean	MAN05
Lifecycle Cost Analysis	results implemented in final construction	boolean	MAN05
Lifecycle Cost Analysis	results implemented in specification	boolean	MAN05
Lifecycle Cost Analysis	shows real and discounted cash flow terms	boolean	MAN05
Lifecycle Cost Analysis	study period	int	MAN05
Lifecycle Cost Analysis	updated during riba stages d or stage e or equivalent	boolean	MAN05
Lift System	has a regenerative drive unit	boolean	ENE06
Lift System	lift cars use energy efficient lighting and display lighting	boolean	ENE06
Lift System	operates in stand by condition during off peak periods	boolean	ENE06
Lift System	used a drive controller capable of variable speed	boolean	ENE06
Lift System	uses a drive controller capable of variable frequency	boolean	ENE06
Lift System	uses a drive controller capable of variable voltage	boolean	ENE06
Low Zero Carbon Feasibility Study	all local lzc unfeasible due to late stage consideration	boolean	ENE04
Low Zero Carbon Feasibility Study	carried out at concept design stage	boolean	ENE04
Low Zero Carbon Feasibility Study	carried out at riba stage c or equivalent	boolean	ENE04
Low Zero Carbon Feasibility Study	carried out by energy specialist	boolean	ENE04
Low Zero Carbon Feasibility Study	carried out later than riba stage c or equivalent	boolean	ENE04
Low Zero Carbon Feasibility Study	completed in accordance with iso14044	boolean	ENE04
Low Zero Carbon Feasibility Study	considers	enum[]	ENE04
Low Zero Carbon Feasibility Study	highlights and justified which lzc energy sources discounted due to late consideration	boolean	ENE04

Topic	Property	IFC Type	Issues Appearing In
Low Zero Carbon Feasibility Study	specification of local lzc technologies is unfeasible	boolean	ENE04
Moving Walk	fitted with load sensing device to synchronise motor to passenger demand	boolean	ENE06
Noise Impact Assessment	conducted by suitably qualified acoustic consultant	boolean	POL05
Noise Impact Assessment	conducted in compliance with bs 7445	boolean	POL05
Noise Impact Assessment	determined existing background noise levels at nearest or closest noise sensitive dwelling	boolean	POL05
Noise Impact Assessment	determined new noise levels at nearest or closest noise sensitive dwelling	boolean	POL05
Operational Waste Facility	compliant with htm07 01	boolean	WST03
Operational Waste Facility	compliant with shtm3	boolean	WST03
Plant	percentage water consumption	double	WAT02
Post Occupancy Evaluation	client has committed to disseminate performance information	boolean	MAN04
Post Occupancy Evaluation	client makes commitment to conduct one year after occupation	boolean	MAN04
Post Occupancy Evaluation	conducted by independent third party	boolean	MAN04
Post Occupancy Evaluation	contains sustainability performance	boolean	MAN04
Post Occupancy Evaluation	disseminated appropriately	boolean	MAN04
Post Occupancy Evaluation	includes feedback on	enum[]	MAN04
Post Occupancy Evaluation	includes review of design and construction process	boolean	MAN04
Prison Cell	volume controller specified on cell water supply	boolean	WAT01
Project	actions taken to protect biodiversity are recorded and made available for public request	boolean	LE05
Project	all building service included in commissioning schedule	boolean	MAN01
Project	all timber used in project is sourced according to uk timber procurement policy	boolean	MAN03
Project	appropriate team member appointed to monitor and program commissioning	boolean	MAN01
Project	appropriate team member appointed to monitor and program precommissioning	boolean	MAN01
Project	art coordinator appointed	boolean	HEA01
Project	art coordinator experience related to	enum[]	HEA01
Project	art coordinator holds relevant qualification	boolean	HEA01
Project	art policy and strategy endorsed at senior management level	boolean	HEA01
Project	art policy and strategy prepared at feasibility design brief stage	boolean	HEA01
Project	authority responsibilitiy and access to data given to indvidual to monitor record and report energy water transport consumption data	boolean	MAN03
Project	breeam accredited professional appointed no later than stage b or equivalent	boolean	MAN01
Project	breeam accredited professional engaged to monitor to attend key meetings during stages b to e	boolean	MAN01
Project	breeam accredited professional engaged to monitor to attend key meetings up stage l equivalent	boolean	MAN01
Project	breeam accredited professional produces reports for client and team detailing progress against targets for each full team meeting	boolean	MAN01,MAN01
Project	breeam performance targets form a requirement of principal contractors contract	boolean	MAN01
Project	breeam targets demonstrably achieved	boolean	MAN01,MAN01
Project	building occupant has contract to supply electricity from an accredited fully renewable source	boolean	ENE04
Project	building total modelled co2 emissions reported via breeam tool	boolean	ENE01
Project	building total modelled operational primary energy consumptions reported via breeam tool	boolean	ENE01
Project	cfsh eco1 achieved using eco1 checklist	boolean	LE02

Topic	Property	IFC Type	Issues Appearing In
Project	change in ecological value calculated using breeam calculator	boolean	LE03
Project	cibse guide energy efficiency measure incorporated	enum[]	ENE08
Project	classcool used to carry out simulation at detailed design stage	boolean	HEA03
Project	client has confirmed that remediation of site carried out in accordance with implementation plan	boolean	LE01
Project	collaborative assessment conducted between developer and tenant	boolean	HEA02
Project	collaborative assessment undertaken between tenant and developer	boolean	ENE03,ENE04
Project	commissioning conducted inline with current standards	boolean	MAN01
Project	commissioning manager appointed during design stage	boolean	MAN01
Project	comprehensive uptodate drainage plan of site made available to occupiers	boolean	POL03
Project	construction waste from construction gate to waste disposal centre gate must be monitored	boolean	MAN03
Project	consultation with suitable qualified security consultant conducted during or prior concept design stage or equivalent	boolean	HEA06
Project	consultation with suitably qualified security consultant conducted	boolean	HEA06
Project	contains demolition	boolean	WST01,WST01
Project	contains new publicly accessible car parks	boolean	HEA06
Project	contents of art strategy and policy	enum[]	HEA01
Project	contents of training provided to occupier or premises manager	enum[]	MAN01
Project	critical appraisal in accordance with iso15686 consducted at feasibility stage	boolean	MAN05
Project	currently in interim design stage of assessment	boolean	MAN01
Project	defined breeam performance targets agreed contractually with client no later than stage c	boolean	MAN01
Project	demonstrated a green building guide for tenant fit outs	boolean	POL01,POL02,POL04,POL05
Project	demonstrated developer tenant collaboration	boolean	POL01,POL02,POL04,POL05
Project	demonstrated use of a tenancy lease agreement between the developer and tenant	boolean	POL01,POL02,POL04,POL05
Project	design team submits bim from impact software to bre global	boolean	MAT01
Project	design team used impact equivalent compliant software tool	boolean	MAT01
Project	development size type such that most deliveries likely to be by small vans	boolean	HEA06
Project	ecologist appointed prior to commencement of activities on site	boolean	LE05
Project	ecologist confirms all uk and eu legislation relating to protection and enhancement of ecology has been compiled with	boolean	LE05
Project	ecologist has estimated site ecological value using desktop information	boolean	LE03
Project	electricity supply contract duration	double	ENE04
Project	energy consumption and co2 emissions from construction reported via breeam scoring and reporting tool	boolean	MAN03
Project	energy consumption of construction site monitored and recorded	boolean	MAN03
Project	energy efficiency measures taken compromise heath and safety	boolean	ENE07
Project	eprnc calculated using breeam ene01 calculator	boolean	ENE01
Project	expands or refurbishes existing public car parks	boolean	HEA06
Project	external lighting strategy has been designed in compliance with table 2 of ilp guidance notes	boolean	POL04
Project	figures used for calculation of reduction provided by low zero carbon technologies based on approved software	boolean	ENE04
Project	final design embodies recommendations of suitably qualified security consultant	boolean	HEA06
Project	formaldehyde concentration and volatile organic compound concentrated reported to bre global	boolean	HEA02
Project	formaldehyde concentration and volatile organic compound concentration measured in accordance with	enum[]	HEA02
Project	fuel consumption co2 emissions and distance travelled must be reported via breeam scoring and reporting tool for construction materials transport	boolean	MAN03
Project	fuel consumption co2 emissions and distance travelled must be reported via breeam scoring and reporting tool for waste materials transport	boolean	MAN03

Topic	Property	IFC Type	Issues Appearing In
Project	glare control strategy developed in tandem with lighting strategy	boolean	HEA01
Project	green building guide explains energy monitoring requirements	boolean	ENE02,ENE03,ENE04
Project	green building guide for tenant fit outs explains volatile organic compound performance requirements	boolean	HEA02
Project	habitat management plan content	enum[]	LE05
Project	habitat management plan produced	boolean	LE05
Project	has an access statement developed	boolean	MAN04
Project	has external consultant facilities manager	boolean	MAN01
Project	has manufacturer declaration of formaldehyde class e1 without testing	boolean	HEA02
Project	has specialist commissioning manager	boolean	MAN01
Project	in final post-construction stage of assessment	boolean	MAN01
Project	information on eu energy efficiency labeling scheme provided for residential aspects	boolean	ENE08
Project	input into breeam ecological value calculator contains	enum[]	LE03
Project	insulation index calculated by mat04 calculator	boolean	MAT04
Project	is built to confirm to secured by design and safer parking	boolean	HEA06
Project	large scale equipment procured in accordance with enc02de chapter 3	boolean	ENE08
Project	lifecycle cost analysis conducted	boolean	MAN05
Project	local wildlife group actions	enum[]	LE05
Project	mat01 points calculated using breeam mat01 calculator	boolean	MAT01
Project	meetings held to define roles responsibilities and contributions held during commissioning and handover	boolean	MAN01
Project	meetings held to define roles responsibilities and contributions held during construction	boolean	MAN01
Project	meetings held to define roles responsibilities and contributions held during design	boolean	MAN01
Project	meetings held to define roles responsibilities and contributions held during occupation	boolean	MAN01
Project	monitor transport of materials for ground works and landscaping from factory gate to building site	boolean	MAN03
Project	monitor transport of materials for major building elements from factory gate to building site	boolean	MAN03
Project	net water consumption from construction reported via breeam scoring and reporting tool	boolean	MAN03
Project	parties involved in decision making process	enum[]	MAN01
Project	partnership establish with local group with wildlife expertise	boolean	LE05
Project	performance factors considered in large scale equipment purchase	enum[]	ENE08
Project	planning authority required survey or statement to be prepared	boolean	LE02
Project	procedure exists to analyse discrepancies with a view to adjusting systems	boolean	MAN01
Project	procedure exists to collect water and energy consumption data for 1 year after occupancy	boolean	MAN01
Project	procedure exists to compare collected energy and water data with expected values	boolean	MAN01
Project	roles and responsibilities considered	enum[]	MAN01
Project	simulation software at detailed design stage provided full dynamic thermal analysis	boolean	HEA03
Project	specialist commissioning agent responsibilities	enum[]	MAN01
Project	suitably qualified ecologist appointed	boolean	LE03,LE05
Project	suitably qualified ecologist appointed to report on ehancement and protection of ecology	boolean	LE04
Project	suitably qualified ecologist used for cfsh assessment	boolean	LE03
Project	tenancy lease agreement between developer and tenant in place stipulating volatile organic compound performance requirements met at fit out stage	boolean	HEA02
Project	tenancy lease agreement stipulated energy monitoring requirements	boolean	ENE02,ENE03,ENE04
Project	thermal modelling carried out in accordance with cibse am11	boolean	HEA03
Project	thermal modelling has informed temperature control strategy	boolean	HEA03
Project	timber sourced in accordance with uk government timber procurement policy	boolean	MAT03
Project	transport resulting from delivery of materials recorded and monitored	boolean	MAN03
Project	type	enum[]	ENE07
Project	water consumption of construction site monitored and recorded	boolean	MAN03
Project	workforce given specific training on how to protect site ecology	boolean	LE05
Project	works programmed to minimise distruption to wildlife	boolean	LE05

Topic	Property	IFC Type	Issues Appearing In
Project	years experience of art coordinator	int	HEA01
Rainwater System	specified and installed in compliance with bs8515	boolean	WAT01
Rainwater System	yield used to offset potable water demands	boolean	WAT01
Recyclable Waste Storage Area	accessible to building occupants	boolean	WST03
Recyclable Waste Storage Area	accessible to facilities operators	boolean	WST03
Recyclable Waste Storage Area	accessible to waste management contractors	boolean	WST03
Recyclable Waste Storage Area	has appropriate capacity for building	boolean	WST03
Recycling Containers	capacity	double	WST03,WST03
Recycling Containers	situated in dedicated non obstructive position	boolean	WST03,WST03
Recycling Policy	items covered	enum[]	WST03,WST03
Recycling Policy	outlines procedures that will be operated	boolean	WST03
Refrigerant System	alarm threshold that triggers pump down upon detection of refrigerant in the plan room	double	POL01
Refrigerant System	automated permanent refrigerant leak detection system is installed covering high-risk parts of the plant	boolean	POL01
Refrigerant System	automatic shutdown and pumpdown occurs on detection of leak or charge loss	boolean	POL01
Refrigerant System	commissioned to comply with criteria commissioning in breeam man1	boolean	ENE05
Refrigerant System	delc co2e calculated by pol01 calculator	boolean	POL01
Refrigerant System	design team confirm complies with bsen378	boolean	POL01,POL01
Refrigerant System	design team confirm complies with institute of refrigeration ammonia code of practice	boolean	POL01
Refrigerant System	design team confirms complies with institute of refrigeration co2 code of practice	boolean	POL01
Refrigerant System	global warming potential of refrigerant	double	POL01
Refrigerant System	leakage charge loss detection system specified which is not based on principle of measuring concentration of refrigerant in air	boolean	POL01
Refrigerant System	meets commercial refrigeration code of conduct	boolean	ENE05
Refrigerant System	pump down into separate storage tank or heat exchanger	boolean	POL01
Refrigerant System	refrigerant charge per unit	int	POL01
Refrigerant System	robust and tested components	enum[]	ENE05
Refrigerant System	using a robust and tested automated permanent refrigerant leak detection system included on eca product list	boolean	POL01
Site Waste Management Plan	audit conducted to determine if refurbishment or reuse is feasible	boolean	WST01
Site Waste Management Plan	contains commitments for minimising non hazardous waste inline with benchmark	boolean	WST01
Site Waste Management Plan	contains details of person responsible for implementation	boolean	WST01
Site Waste Management Plan	contains monitoring measuring and reporting procedures for waste	boolean	WST01
Refrigerant System	robust and tested components	enum[]	ENE05

Topic	Property	IFC Type	Issues Appearing In
Site Waste Management Plan	contains procedures for minimising non hazardous waste inline with benchmark	boolean	WST01
Site Waste Management Plan	contains procedures to maximize recovery of material from demolition	boolean	WST01
Site Waste Management Plan	contains target benchmark for resource efficiency	boolean	WST01
Site Waste Management Plan	pre demolition audit covers identification of key refurbishment demolition materials	boolean	WST01
Site Waste Management Plan	pre demolition audit covers potential applications and issues for refurbishment/ demolition materials	boolean	WST01
Site Waste Management Plan	stage	enum	WST01
Space	active cooling temperature threshold	double	ENE08
Space	adequate view out is provided from standing and sitting position	boolean	HEA01
Space	breeam room depth criterion is satisfied	boolean	HEA01
Space	clinical area where control of environment or operations prevent a view out being provided	boolean	HEA01
Space	close work or visual aids undertaken	boolean	HEA01
Space	co2 sensors alert operative	boolean	HEA02
Space	co2 sensors linked to controls to adjust quantity of fresh air	boolean	HEA02
Space	co2 sensors linked to ventilation system providing demand controlled ventilation	boolean	HEA02
Space	computer screens regularly used	boolean	HEA01
Space	contains a centrally located nurses base	boolean	HEA01
Space	contains workstations for security observation	boolean	HEA01
Space	contains workstations or benches	boolean	HEA01
Space	design of natural ventilation demonstrated that provides adequate cross floor air ventilation rates	boolean	HEA02
Space	design of natural ventilation is done by tool types recommended by cibse am10	boolean	HEA02
Space	exclusion of natural light is a functional requirement	boolean	HEA01
Space	forced ventilation temperature threshold	double	ENE08
Space	has air quality sensors	boolean	HEA02
Space	has easily accessible occupancy ventilation controls	boolean	HEA02
Space	has formal lectern demonstration or performance area	boolean	HEA01
Space	has lighting controls in accordance with cibse lighting guide 5	boolean	HEA01
Space	has openable windows	boolean	HEA02
Space	has potential to have higher level of fresh air supply that removes short term odours and prevents overheating	boolean	HEA02
Space	has potential to have lower level fresh air supply to meet needs for good air quality	boolean	HEA02
Space	has stepped seating	boolean	HEA01
Space	has view of sky from desk height	boolean	HEA01
Space	is functional	boolean	HEA02
Space	is in location where a view out is deemed of benefit to occupants	boolean	HEA01
Space	is it intensive area	boolean	ENE08
Space	is occupied	boolean	HEA01
Space	is show area	boolean	WST04
Space	lighting controls easily accessible for teacher	boolean	HEA01
Space	lighting design complies with cibse lighting guide 7	boolean	HEA01
Space	likely to be occupied by workstations benches or desks	boolean	HEA01
Space	luminance of luminaires limited to avoid screen reflection	boolean	HEA01
Space	lux levels compliant with cibse code of lighting for 2009	boolean	HEA01
Space	maintained illuminance	double	HEA01
Space	maximum distance of positions from a wall with window or permanent opening with an adequate view out	int	HEA01
Space	number of levels of user control on supply of fresh air	int	HEA02
Space	occupancy pattern	enum[]	HEA02
Space	occupant can lower level of lighting	boolean	HEA01
Space	openable window area in percentage of gross internal floor area	double	HEA02
Space	openable window area on opposite sides and evenly distributed	boolean	HEA02

Topic	Property	IFC Type	Issues Appearing In
Space	percent of working plane with view of sky	int	HEA01
Space	percentage ventilation use as shown by design calculations	double	HEA02
Space	potential for disabling glare designed out	boolean	HEA01
Space	recommendations for average wall illuminace are followed	boolean	HEA01
Space	recommendations for ceiling illuminance are followed	boolean	HEA01
Space	recommendations for direct lighting are followed	boolean	HEA01
Space	recommendations for lit ceiling are followed	boolean	HEA01
Space	tenanted	boolean	WST04
Space	type	enum[]	WAT02,WAT02,WAT02
Space	type	enum	HEA01
Storage and Delivery Areas	designed and detailed in accordance with application recommendations	boolean	POL03
Storage and Delivery Areas	stores	enum[]	POL03,POL03
Swimming Pool	air temperatures can be controlled to within one degree	boolean	ENE08
Swimming Pool	has automatic closing liquid pool covers	boolean	ENE08
Swimming Pool	has automatic pool covers	boolean	ENE08
Swimming Pool	has semi automatic pool covers	boolean	ENE08
Thermographic Survey	any defects identified by survey are rectified	boolean	MAN01
Thermographic Survey	conducted by a professional holding level 2 certificate in thermography	boolean	MAN01
Thermographic Survey	conducted in accordance with appropriate standard	boolean	MAN01
Thermographic Survey	conducted once construction is complete	boolean	MAN01
Thermographic Survey	confirms avoidance of air leakage paths through fabric	boolean	MAN01
Thermographic Survey	confirms avoidance of excessive thermal bridging	boolean	MAN01
Thermographic Survey	survey confirms continuity of insulation in accordance with construction drawings	boolean	MAN01
Water Pollution Prevention System	designed and detailed in accordance with applicable recommendations	boolean	POL03
Water Supply	has leak detection alarm that is audible when activated	boolean	WAT03
Water Supply	has leak detection that is programmable to suit water consumption criteria	boolean	WAT03
Water Supply	Leak detection able to identify different leakage rates	boolean	WAT03
Water Supply	Leak detection activated when flow of water is above pre set flow rate for a pre set period of time	boolean	WAT03
Water Supply	leak detection capable of detecting a major water leak between building and utilities water meter	boolean	WAT03
Water Supply	Leak detection designed to avoid false alarms caused by normal operation of large water consuming plant	boolean	WAT03
WC Unit	flushing control activated by electronic sensors	boolean	WAT01
WC Unit	flushing control suitable for patients with frail or infirm hands	boolean	WAT01
Window	distance from source of external pollution	double	HEA02
Window	openable	boolean	HEA02

Table 11-2 Data assessed using procedures

Topic	Property	IFC Type	Issues Appearing In
Building	accessibility index calculated using	enum[]	TRA01
Building	air conditioning or refrigeration systems installed	boolean	POL01
Building	all fluorescent lamps fitted with high frequency ballasts	boolean	HEA01

Building	building services	enum[]	MAN01
Building	consists of individual bedrooms and communal facilities	boolean	WST03
Building	contains containment devices	boolean	ENE07
Building	contains escalators	boolean	ENE06
Building	contains fume cupboards	boolean	ENE07
Building	contains laboratory space	boolean	ENE07
Building	contains lifts	boolean	ENE06
Building	contains moving walks	boolean	ENE06
Building	contains self contained dwellings	boolean	MAN02
Building	contains vessels for composting	boolean	WST03
Building	cyclist facilities	enum[]	TRA03
Building	energy consuming systems present	enum[]	ENE02
Building	external lighting specified	boolean	ENE03
Building	external spaces present	boolean	MAN05
Building	greywater system specified	boolean	WAT01
Building	has cold storage facilities	boolean	ENE05
Building	has containment level 3 laboratory	boolean	HEA02
Building	has external areas	boolean	HHEA06
Building	has external lighting	boolean	POL04
Building	has office areas	boolean	POL02
Building	has operational areas	boolean	POL02
Building	has refrigeration for food	boolean	ENE05
Building	has residential areas	boolean	MAN04
Building	has separate heating systems for dwellings	boolean	POL02
Building	has services present	boolean	MAN05, MAN05
Building	has swimming pool	boolean	WAT02
Building	has vehicle wash system	boolean	WAT04
Building	has waste compactor or baler	boolean	WST03
Building	has water heating	boolean	POL02
Building	has water meter fitted	boolean	WAT02, WAT02
Building	heat load	double	POL02
Building	is highly insulated	boolean	POL02
Building	is single occupancy	boolean	ENE02
Building	is supermarket	boolean	ENE05
Building	lab area	double	ENE07
Building	location	enum	WST03
Building	meet requirements of sliding scale compliance	boolean	TRA03
Building	no floors	int	HEA01,HEA01
Building	non recyclable waste storage provided	boolean	WST03
Building	number of bedrooms	boolean	WST03
Building	number of car parking spaces	int	TRA01
Building	number of cycle spaces	int	TRA01
Building	on a prison site	boolean	TRA01
Building	percentage of prison cell complying with external viewing requirements	double	HEA01
Building	rainwater system specified	boolean	WAT01
Building	requires use of refrigerants within plant/systems	boolean	POL01

Table A-113 Data mapped to IFC directly

Topic	Property	IFC Type	Issues Appearing In
Building	cfsh assessed	boolean	POL02
Building	cfsh wat 2 achieved	boolean	WAT04
Building	credits achieved for code for sustainable homes man2	int	MAN02
Building	external space lighting ene6 cfsh credit achieved	boolean	ENE03
Building	has space cooling	boolean	POL02
Building	has space heating	boolean	POL02,POL02,POL02
Building	naturally ventillated	boolean	MAN01
Dwelling	cfsh assessed	boolean	POL03
Dwelling	cfsh issue ene4 achieved	boolean	ENE09
Dwelling	csh was1 credits awarded	int	WST03, WST03
Dwelling	csh was3 credit awarded	int	WST03
External Lighting	power consumption	double	ENE03
Project	achieved credit csh hea1	boolean	HEA01
Project	cfsh eco 3 achieved	boolean	LE02
Project	cfsh eco1 achieved	boolean	LE02
Project	cfsh man4 achieved	boolean	HEA06
Project	cfsh sur 1 additional suds credit awarded	boolean	POL03
Project	cfsh sur2 flood risk credits awarded	boolean	POL03
Storage and Delivery Areas	located externally	boolean	POL03

Table 11-4 Data assessed using external applications

Topic	Property	IFC Type	Issues Appearing In
Building	access level height	double	POL03
Building	category consuming significant majority or unregulated energy	enum	ENE08
Building	daytime resultant noise level difference	double	POL05
Building	eprnc	double	ENE01
Building	flood level height	double	POL03
Building	height of ground level	double	POL03
Building	insulation index	double	MAT04
Building	nighttime resultant noise level difference	double	POL05
Building	nox emission	double	POL02,POL02
Development Site	access level height above flood level	double	POL03
Refrigerant System	delc co2e	double	POL01
Space	area complying with daylight factor	double	HEA01,HEA01
Space	daylight factor	double	HEA01,HEA01
Space	nox emission	double	POL02,POL02,POL02
Space	uniformity ratio	double	HEA01

Appendix B Decision Logic example ENE1

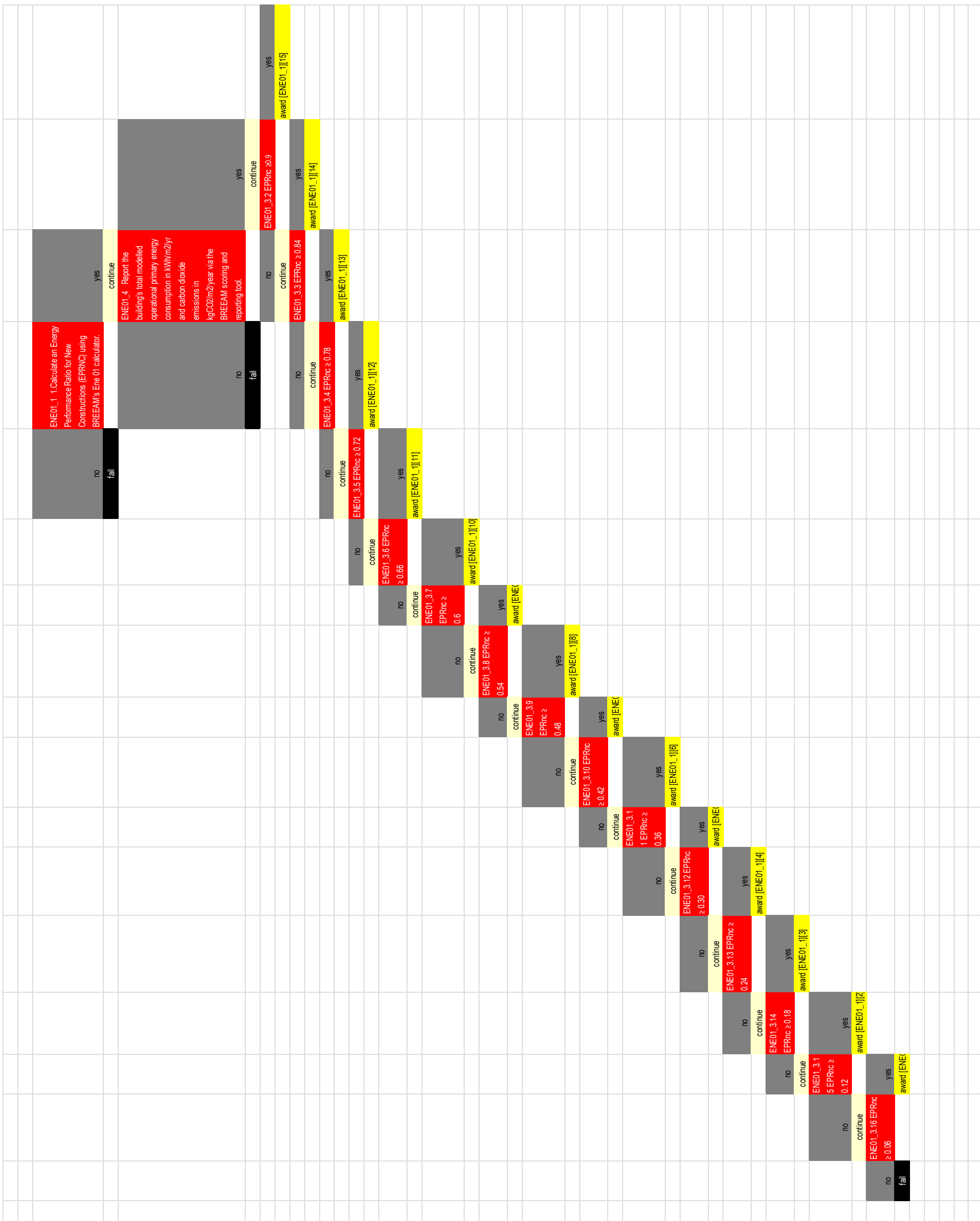

Figure B-1 Decision logic example

Apendix C Rules generation example

Figure 13-1 Rules generation ENE 1


```
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type="text/css" href="style.css"?><regulation><regulation
id="ENE01_1">1.<requirement comparison="=" object="Project" property="eprnc
calculated using breeam ene01 calculator" unit=" " value="true">Calculate an Energy
Performance Ratio for New Constructions (EPRNC) using BREEAMs Ene 01
calculator</requirement>.</regulation><br/><regulation id="ENE01_4"><requirement
comparison="=" object="Project" property="building total modelled operational
primary energy consumptions reported via breeam tool" unit=" " value="true">Report
the buildings total modelled operational primary energy consumption</requirement>
in kWh/m2/yr and <requirement comparison="=" object="Project" property="building
total modelled co2 emissions reported via breeam tool" unit=" " value="true">carbon
dioxide emissions</requirement> in kgCO2/m2/year via the BREEAM scoring and
reporting tool.</regulation><br/><regulation id="ENE01_3.2">EPRnc <requirement
comparison="&gt;=" object="Building" property="eprnc" unit=" "
value="0.9">0.9</requirement></regulation><br/><regulation id="ENE01_3.3">EPRnc
<requirement comparison="&gt;=" object="Building" property="eprnc" unit=" "
value="0.84"> 0.8</requirement>4</regulation><br/><regulation id="ENE01_3.4">EPRnc
<requirement comparison="&gt;=" object="Building" property="eprnc" unit=" "
value="0.78"> 0.7</requirement>8</regulation><br/><regulation id="ENE01_3.5">EPRnc
<requirement comparison="&gt;=" object="Building" property="eprnc" unit=" "
value="0.72"> 0.</requirement>72</regulation><br/><regulation id="ENE01_3.6">EPRnc
<requirement comparison="&gt;=" object="Building" property="eprnc" unit=" "
value="0.66"> 0.6</requirement>6</regulation><br/><regulation id="ENE01_3.7">EPRnc
<requirement comparison="&gt;=" object="Building" property="eprnc" unit=" "
value="0.6"> 0.</requirement>6</regulation><br/><regulation id="ENE01_3.8">EPRnc
<requirement comparison="&gt;=" object="Building" property="eprnc" unit=" "
value="0.54"> 0.</requirement>54</regulation><br/><regulation id="ENE01_3.9">EPRnc
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value="0.48"> 0.</requirement>48</regulation><br/><regulation id="ENE01_3.10">EPRnc
<requirement comparison="&gt;=" object="Building" property="eprnc" unit=" "
value="0.42"> 0.4</requirement>2</regulation><br/><regulation id="ENE01_3.11">EPRnc
```

Apendix D- Decision Tree example

Figure 14-1 ENE 1 Decision Tree