Graph-based Ontology Reasoning for Formal Verification of BREEAM Rules

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ABSTRACT

Globally, the need to check regulation compliance for sustainability has become central in the delivery of construction projects. This is partly due to policies by various governments requiring existing and new buildings to comply with certain standards or regulations. However, the verification of whether a building complies with any particular standard or regulation has proven challenging in practice. The purpose of formal verification is to prove that under a certain set of assumptions, a building will adhere to a certain set of requirements, for example the minimum performance standards of key environmental issues. Compliance checking requires different criteria often difficult to straightforwardly define and combine in an integrated fashion for providing holistic interpretation to facilitate easy decision-making. Such criteria, their various flows and combinations can easily be dealt with using conceptual graph theories and Semantic Web concepts which allow rules to be imbued to facilitate reasoning. The aim of this study is to tap on conceptual graphs and Semantic Web concepts to develop a system for checking Building Research Establishment Environmental Assessment Methodology (BREEAM) sustainability standard compliance in the French construction industry. A conceptual graph-based framework that formally describes BREEAM requirements and visually analyse compliance checking processes has been proposed. When implemented in a software that integrates conceptual graphs and Semantic Web knowledge, automatic reasoning allows both the logical specification and the visual interpretation to be displayed and further provides a semantic support for compliance checking information.

Keywords: Data, Information; Knowledge; Reasoning; Building; Sustainability.

1. Introduction

The construction industry plays a very important role in the development of every country. However, its negative impacts on communities are quite significant especially when compared with other sectors. Nowadays, considerations addressing climate change, fossil fuels depletion and energy security underscore the need for a more sustainable built environment in order to decrease energy consumption and emissions from the construction industry (Soares et al., 2017). For instance, in its energy efficiency action plan, the French government has set important measures for energy savings in many sectors including residential, transport, industry, agricultural sectors in order to comply with article 24 of Directive 2012/27/EU of the European Parliament and the Council of 25th October 2012 on energy efficiency (NEEAP, 2014). Many organizations and governments have developed codes and compliance standards that can aid in obtaining a more sustainable built environment. ISO 50001 supports organizations in all sectors to use energy more efficiently, through the development of an energy management system. Different countries have developed country-specific standards, although in practice their uses of these are often international with some countries using those of others. Amongst the leading standards are BREEAM (UK), LEED (USA), PassiveHaus (Germany), Minergie (Switzerland) and Haute Qualité Environnementale (HQE) (France). While the specifics of these standards vary, they generally tend to specify the criteria for managing the impacts on the outdoor environment and creating a pleasant indoor environment. The plethora of criteria required by these standards is complex to implement including compliance verification. BREEAM is the world's leading design and assessment methods for sustainable buildings, which its use is gradually becoming common in the French construction industry.

Usually, compliance requirements about processes stem from diverse sources such as laws, regulations, or guidelines and an essential challenge is the interpretation of these requirements as compliance objectives and the subsequent specification as compliance rules or constraints (Linh et al., 2015). However, users cannot rely on their visual ability to ensure building information models are of good quality and adhere to standard requirements for the potential use of federated models and versioning (Solihin et al., 2016). These problems are further exacerbated by the complexity of modern buildings comprising of so many parts, technologies and properties. Integrated and transparent descriptions of the dynamics and main drivers of energy supply and demand in buildings are important for a better understanding of energy and environmental requirements in the building sector (Soares et al., 2017). To summarize, given the stringent clients' expectations, too many compliance criteria, so many building components, a manual compliance checking task can be too daunting. Thus, innovative automatic techniques that minimize human intervention are highly recommended (Nawari, 2012). The building construction regulation compliance checking may be enriched by knowledge representation and reasoning principles that directly integrate the terminology formalization, rule engines and visualization of verification results in a dedicated tool for creating and managing building information models (Zhong et al., 2015). These principles are really useful for supporting construction quality compliance verification (Zhong et al., 2012) and aiding design description and checking processes (e.g. acoustic compliance checking (Pauwels et al., 2011)). In this context, using a visual compliance rule graph language for modelling compliance rules can possibly illustrate the compliant and non-compliant events in a user-friendly way (Knuplesch et al., 2017).

The aim of this study is to formalize requirements specification and knowledge representation associated with the effort to check regulation compliance of new and existing buildings in alignment with their digital building models. Semantic Web technologies can be exploited in representing knowledge about domains and facilitate system decision-making. The research objectives are:

- Formal representation of BREEAM requirements using conceptual graph rules
- Formal representation of building information models using conceptual graph facts
- Reasoning over conceptual graphs for compliance checking with BREEAM requirements

To facilitate understanding, the remainder of this paper is divided into 4 sections. Section 2 provides a background of sustainability assessment standards of various countries used in the construction industry. Section 3 presents the proposed approach for graph-based semantic modelling of BREEAM rules. Section 4 describes the formalisation of BREEAM requirements using conceptual graph rules. In section 5 an analysis of major issues covered in this study and the conclusion of the paper are presented.

2. Sustainability assessment standards, knowledge representation and regulation-compliance checking

2.1 Sustainability assessment standards

The global need to properly integrate sustainability requirements in buildings has led to the invention of a number of innovative solutions by different organizations at national and international levels. Sustainability standards or certifications are amongst the leading innovative solutions for driving sustainability in the construction industry. There are many diverse certifications that are used for assessing the environmental performance of buildings. Different countries have developed different standards, although there is no restriction on usage across different geographical boundaries (Cole and Valdebenito, 2013). The leading standards and their countries of origins are Haute Qualité Environmentale (HQE) (France), Building Research Establishment Environmental Assessment Method (BREEAM) (UK), Leadership in Energy and Environmental Design (LEED) (USA), Minergie (Switzerland), Passivhaus (Germany), DGNB (Germany), R-2000 (Canada) and Green Start (Australia). In France, HQE has been traditionally used by the construction industry since its creation. However, recently, BREEAM is also becoming common in use on projects in France. Introduced in 1990, the BREEAM certification is the oldest rating tool, and its influence extends beyond the British territory. Indoor environment quality, energy, and material are the main focus in green rating systems and BREEAM is considered (through its assessment capacity of sustainable factors) as the strongest rating system at present" (Doan et al., 2017). BREEAM and HQE certifications can be used for the construction phase and building operational phases of a project. BREEAM provides a final percentage mark with five grades ('Pass', 'Good', 'Very Good', 'Excellent' and 'Outstanding') (See (BRE Global Ltd, 2015)).The six steps for determining a BREEAM rating includes (BRE Global Ltd, 2018):

a. For each of BREEAM's ten categories (management, health and wellbeing, energy, transport, water, materials, waste, land use and ecology, pollution and innovation), the number of credits awarded is determined by the BREEAM assessor according to the number of credits available when the criteria of each assessment issue have been met (as detailed in the technical sections of this document);
b. The percentage of available credits achieved is calculated for each section;
c. The percentage of credits achieved in each section is multiplied by the corresponding weighting for each section to give the overall environmental category score;
d. The scores of each section are added together to give the overall BREEAM score;
e. The overall score is compared to the BREEAM rating benchmark levels and, provided all minimum standards have been met, the relevant BREEAM rating is achieved;
f. An additional 1% can be added to the final BREEAM score for each innovation credit achieved (up to a maximum of 10% with the total BREEAM score capped at 100%).

The numbers in the BREEAM certification represent the number of credits available for an individual assessment issue. The meaning of the percentages associated with the star evaluation system (see Table 1) is the percentage of available credits achieved in comparison to the number of credits available for each BREEAM section.

Grading		**Percentage**
Pass	★	≥30%
Good	★★	≥45%
Very good	★★★	≥55%
Excellent	★★★★	≥70%
Outstanding	★★★★★	≥80%

Table 1: BREEAM rating benchmarks [Adapted from (BRE Global Ltd, 2015)]

An example BREEAM score and rating calculation is described in table 2.

BREEAM Section	**Credits Achieved**	**Credits Available**	**% of Credits Achieved**	**Category weighting (fully fitted)**	**Section Score**
Management	10	21	52.38%	0.14	7.38%
Health and Well-being	14	22	63.64%	0.15	9.40%
Energy	16	31	51.61%	0.21	10.74%
Transport	10	12	83.33%	0.08	6.71%
Water	7	10	70.00%	0.07	4.70%
Materials	5	14	35.71%	0.09	3.36%
Waste	6	6	100.00%	0.04	4.03%
Land Use and Ecology	5	10	50.00%	0.07	3.36%
Pollution	8	13	61.54%	0.09	5.37%
Innovation	2	10	20.00%	0.07	1.34%
Final BREEAM score			56.38%		
BREEAM Rating			VERY GOOD		

Table 2: An example of BREEAM score and rating calculation (BRE Global Ltd, 2018)

Although the sustainability assessment methods require some adaptation to be more effective (Sharifi and Murayama, 2013), the assessment scope of BREEAM and LEED are found most comprehensive in building environmental schemes (Lee, 2013). As BRE (2017) suggests, it is imperative investigating how to improve compliance verification of buildings. In the context of sustainability regulations and among other standards, BREEAM was chosen because of its richness in information content which can be exploited in reasoning when integrated with building model for regulation compliance. BREEAM scheme document for non-domestic buildings covers many items on how to reduce life cycle impact of new buildings on the environment (BRE Global Ltd, 2016). For instance, the aim of the *management construction site impacts* criteria is to "recognize and encourage construction sites managed in an environmentally sound manner in terms of resource use, energy consumption and pollution" (BRE Global Ltd, 2016). To ensure performance against fundamental environmental issues is not ignored in pursuit of a particular rating, BREEAM sets minimum standards of performance in key areas, e.g. energy, water, waste, etc. These minimum standards mean that particular credits or criteria must be achieved for a specific BREEAM rating. The minimum acceptable levels of performance for each rating are summarised in Table 3.

	Minimum standards by BREEAM rating level				
BREEAM issue	**Pass**	**Good**	**Very Good**	**Excellent**	**Outstanding**
Man 03 Responsible construction practices	None	None	None	One credit (responsible construction management)	Two credits (responsible construction management)
Man 04 Commissioning and handover	None	None	None	Criterion 11 (Building User Guide)	Criterion 11 (Building User Guide)
Man 05 Aftercare	None	None	None	One credit (commissioning-implementation)	One credit (commissioning-implementation)
Ene 01 Reduction of energy use and carbon emissions	None	None	None	Four credits	Six
Ene 02 Energy monitoring	None	None	One credit (First sub-metering credit)	One credit (First sub-metering credit)	One credit (First sub-metering credit)
Wat 01 Water consumption	None	One credit	One credit	One credit	Two credits
Wat 02 Water monitoring	None	Criterion 1 only	Criterion 1 only	Criterion 1 only	Criterion 1 only
Mat 03 Responsible sourcing of materials	Criterion 1 only	Criterion 1 only	Criterion 1 only	Criterion 1 only	Criterion 1 only
Wst 01 Construction waste management	None	None	None	None	One credit
Wst 03 Operational waste	None	None	None	One credit	One credit

Table 3: Minimum BREEAM standards by rating level (BRE Global Ltd, 2018)

In each BREEAM criterion, the number of credits available, the aim of the criteria, the assessment criteria, the compliance notes about it and also additional information are explained. In practice, BREEAM compliance checking is conducted by a professional assessor. The professional assessor observes a chosen building and then manually grades the various BREEAM criteria based on observation. This approach is highly subjective, error prone and time-consuming.

2.2 Knowledge representation

Many knowledge representation models typically use ontologies to support information analysis, retrieval, and sharing. The most generally accepted and widely used definition of ontology is that of Gruber (1995) who defined it as "a specification of a representational conceptualization for a shared domain of discourse – definitions of classes, relations, functions, and other objects". In other words, an ontology can be thought of as a specification of how the knowledge of a particular domain can be modelled (represented, described or structured) and shared (Alesso and Smith, 2009; Milton, 2007) with representational primitives (e.g. classes, attributes, etc.). Knowledge representation models (e.g. Description Logics or conceptual graphs) allow the description of formal ontologies with their underlying logical semantics providing a set of reasoning mechanisms to facilitate system decision support (Tah and Abanda, 2011). Conceptual Graphs and Resource Description Framework (RDF) are similar graph-based knowledge representation methods in which models are described by nodes connected with arcs. In Conceptual Graphs, concept nodes are linked by conceptual relationship arcs while in RDF, resource nodes are linked to properties. Hence, a semantic converter has been introduced for converting knowledge modelled in Conceptual Graphs into RDF (Yao and Etzkorn, 2006). For instance, the translations between RDF and Conceptual Graphs can basically convert each triplet RDF in a ternary relation where each of the concept nodes of the relation will characterize the RDF triplet elements (Baget et al., 2009). Such automated conversion between these knowledge representation formats allows tools like Cogui (representing Conceptual Graphs in the CoGXML format) to import RDF Schema or RDF(S) documents and to export RDF(S) documents. The main idea behind the intuitive translation from RDF to Conceptual Graphs is to exploit as much as possible the clear separation between ontology and data. So, there is a focus on the RDF subset in which the three sets of individual markers or instances, relation and concept types are disjoint. The intuitive correspondences between RDF, Conceptual Graphs and logic are described in the table 4.

RDFS Triple	*Equivalent Conceptual Graphs*	*Logical Translation*
C rdf:type rdfs:Class	*C* concept type	*C* unary predicate
R rdf:type rdf:Property	*R* binary relation type	*R* binary predicate
C rdfs:subClassOf *D*	$C \leq D$	$\forall x\ (C(x) \rightarrow D(x))$
R rdfs:subPropertyOf *S*	$R \leq S$	$\forall x \forall y\ (R(x, y) \rightarrow S(x, y))$
R rdfs:domain *C*	$\sigma\ (R) = (C, -)$	$\forall x \forall y\ (R(x, y) \rightarrow C(x))$
R rdfs:range *D*	$\sigma\ (R) = (-, D)$	$\forall x \forall y\ (R(x, y) \rightarrow D(y))$

Table 4: Correspondences between RDF, Conceptual Graphs and logic (Baget et al., 2010).

This transformation is achieved through the following principles (Baget et al., 2010):

- the acknowledgement of the distinction between the basic component of an ontology with the translation of classes into concept types, properties into binary relations, and instances into individual markers;
- the preservation of the visual appeal and formal meaning of conceptual graphs;

- the clear differentiation between ontology and data.

2.3 Regulations compliance checking

In practice the development of regulatory compliance systems involves the understanding of three semantic contexts namely the target domain, the regulations being considered and the data format to be checked for compliance (Beach et al., 2015). Furthermore, efforts should be made to improve the output of the automated regulations to enhance the generation of human readable documentation in compliance checking processes. The linking of the graph configuration with the semantic web and rule languages has led to the improvement of a rule checking environment for the construction industry (Pauwels et al., 2011). For the purpose of automated checking of rules, the requirement for formalisation of regulations can be addressed using an ontology through a formal knowledge representation like conceptual graph (CG) for analysis and break-down of complex rules into atomic rules and constraints. The formalized organization of domain knowledge is useful to support defining clear data modules and creating manageable relationships among concepts using semantic reasoning (Lee et al., 2016). For instance, there are existing weaknesses in knowledge representation approaches which lack the graphical expressiveness and visual reasoning. Hence, there is a crucial need to improve the effective demonstration in displaying the required properties and the compliance checking procedures with an intermediary representation that can easily be understood by domain experts. With regard to the usability of a domain specific knowledge representation language, the graphical expressiveness is useful to strengthen the simplicity and intuitiveness of various formal reasoning opportunities (queries or rules). Three rule-checking approaches (i.e. coded rule-checking, rule-checking by querying and dedicated rule language) have been described for semantic rule-checking in the construction industry (Pauwels and Zhang, 2015). Knowledge inference is mainly supported by the approach using dedicated rule languages in which the rules are described using logical operators (OR, AND, NOT) within declarative IF-THEN statements. The combination of rule-checking techniques (direct or indirect connection) with accessible Building Information Modeling (BIM) software can vary and evolve depending upon the level of support for semantic analysis. With regards to the querying and reasoning over large scale building datasets, there are certain aspects that impact the performance results in handling these datasets. The key aspects impacting the query performance results in implementation procedures are: (i) indexing algorithms, query rewriting techniques, and rule management strategies, (ii) forward-chaining versus backward-chaining, (iii) the dependency on the kind of data available in the models, (iv) the effect of using a triple store or RDF store and (v) the dependency on the number of output results (Pauwels et al., 2016).

3. Proposed graph-based semantic modelling of BREEAM rules approach

3.1 Research method framework

The proposed framework is built on conceptual graphs, since they provide different building blocks for expressing diverse sorts of knowledge: facts, queries, rules representing both implicit and explicit knowledge. This formal richness of expressing diverse knowledge combined with the visual representation facilitate rule representation and checking including other high-level computational querying tasks often used by domain experts to verify the correctness of the BREEAM rule knowledge-base.

In the context of the proposed compliance checking approach illustrated in Figure 1, the reasoning mechanism implemented is mainly based on a comparison of conceptual graphs with the mechanism of graph homomorphism.

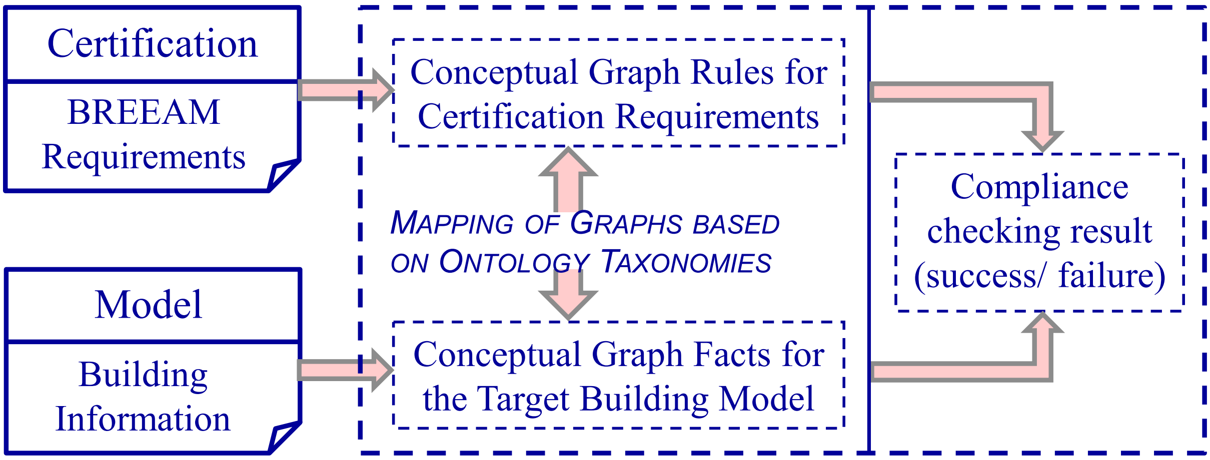

Figure 1: The proposed graph-based approach for compliance checking

Graph homomorphism is a technique used to check whether a given graph is more specific than the other, by specifying general concepts and relations towards more specific concepts and relations. Graph homomorphism is applied in the area of construction rules management to find compliance between building requirements (e.g. BREEAM) and building information of a target building. The existence of such mapping, based on ontology concepts between associated conceptual graphs shows a compliance checking result (success or failure) for the target building model.

3.2 Semantic modelling with conceptual graphs

Our choice for knowledge modelling is underpinned by the conceptual graphs formalism (Sowa, 2000). Indeed, on the one hand, it allows the formalization of conceptual and inferential knowledge of a target domain. On the other hand, the provided reasoning tools facilitate the visualization, the enrichment and the verification of the modelled knowledge by end users (Chein et al., 2013). In the context of the semantic web, the conceptual graphs can play a pivotal role for some knowledge representation languages, while ensuring the interoperability and the complementarity of modes of reasoning. In terms of syntactic interoperability, the Conceptual Graphs eXtensible Markup Language (CoGXML) format is a valid and well-formed representation of conceptual graphs in XML documents (Carloni et al., 2009). A CoGXML file contains an XML header and declarations of ontological vocabularies (a set of partially ordered concept types, relation types, nested types, signature of relation types and conformity relations), graphs and rules. Concerning, the links with other knowledge representation languages, there is a bidirectional correspondence (Yao and Etzkorn, 2006) between conceptual graphs and RDFS language (Cyganiak et al., 2014). Hence, a two-way communication can be used to connect the conceptual graphs to semantic web languages built upon RDF like the Web Ontology Language (OWL) (Horrocks et al., 2005; Grau et al., 2008). Furthermore, a connection between conceptual graphs (a subclass corresponds to trees) and description logics (DLs) (Baader et al., 1999) has been established with the latter being the most implemented language in various knowledge base applications. There is also a link between conceptual graphs and the Semantic Web Rule Language (SWRL) that combines OWL-DL with a subset of the Rule Markup Language (i.e. a subset of Datalog) (Mei and Boley, 2006). These Semantic Web languages (e.g. OWL and SWRL) can perfectly be used to build a rule system, but many tools implementing them lack graphical user interfaces limiting their usability by domain experts (Li and Tian, 2011).

3. 3 Knowledge representation: A conceptual graph approach

The appropriate processing of formal compliance checking requires the use of knowledge representation language having a well-defined syntax and a formal semantics. The conceptual graph (CG) formalism (Sowa, 1984) can be considered as a compromise representation between a formal language and a graphical language as it is visual and has a range of reasoning potentials. Visual languages carry great symbolic meaning in human cultures and range from informal ambiguous sketches to rigorously defined technical diagrams. They have become a key component of human-computer interaction. Conceptual graph operations provide formal reasoning tools that ensure reliability and enhance the quality of construction knowledge-based systems. These are critical factors for their successful use in real-world applications. For instance, these reasoning tools can help the user to produce new pieces of knowledge or determine whether a knowledge-based system satisfies its purely formal specifications (Kamsu-Foguem, 2012). According to Chein and Mugnier (2009), the basic components of knowledge representation using conceptual graphs (see figure 2) consist of:

- ontological knowledge comprising relation types with their signatures and concept types with also the possibility of implementing multiple inheritance and a set of possible individuals and nesting types for embedded concepts having an internal description;
- factual knowledge that is a set of conceptual graphs built from components (concepts with their individuals, relations and nesting) available on the ontological knowledge;
- inferential knowledge, which contains conceptual graph rules for inference, each of which is expressed in the form of an implication between an antecedent (hypothesis) and a consequent (conclusion). This could eventually be completed by a set of queries and constraints.

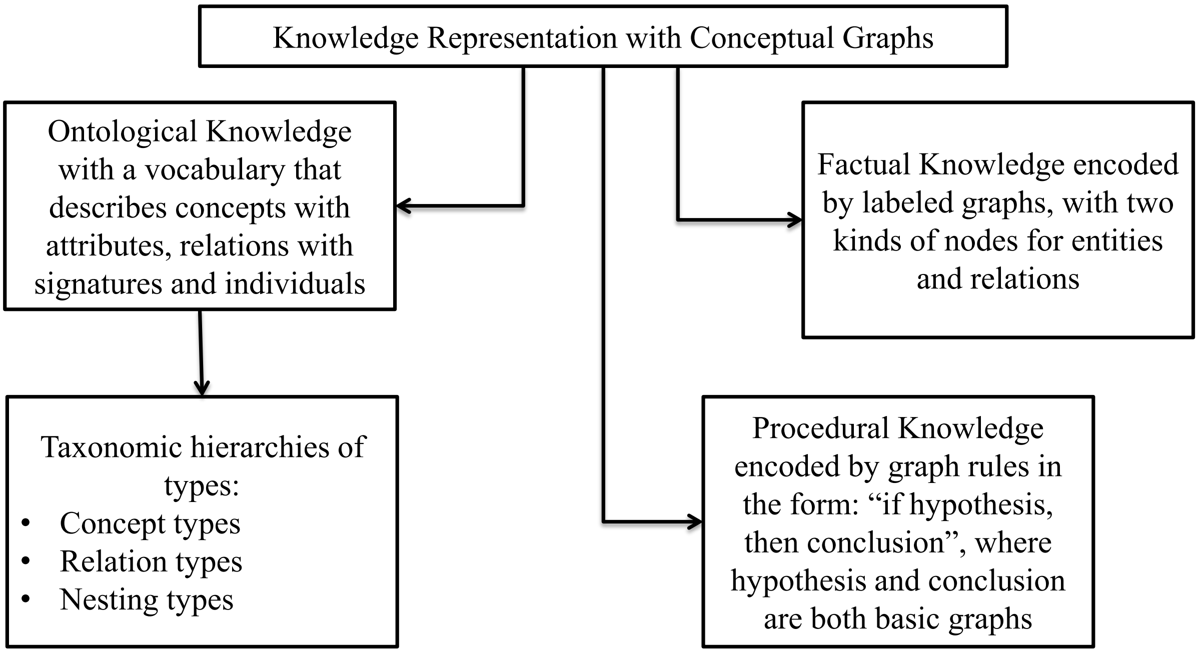

Figure 2: Knowledge representation using conceptual graphs

3.4. Implementation in CoGui

The proposed work is modelled on the conceptual graph formalism by using CoGui. This software is a free *graph-based* visual tool, developed in Java, for building Conceptual Graph knowledge bases represented in the CoGXML format that allows representation of conceptual graphs in the format of XML documents. As described in Buche et al. (2014), CoGui is currently used in research laboratories and universities in France for visual manipulation of conceptual graphs. Based on the conceptual graph model, CoGui is a graphical tool for representation of knowledge and reasoning. This free tool was developed in Java for contributing to the construction of knowledge bases using conceptual graphs. The knowledge bases are represented in an exchange format called CoGXML. CoGui allows us to create a knowledge base, to edit its terminological support, its base of facts and rules. The wizards provided by this software make it possible to analyse facts and to verify whether they respect a certain number of constraints, but also to interrogate them by taking into account the inferences allowed by the inferential knowledge encoded by conceptual graph rules. It includes a Java-like scripting language within its development environment, which allows users to perform various tasks. It is a flexible environment having the following features: (i) Dynamic execution with additional scripting conveniences, (ii) Transparent access to Application Programming Interfaces (APIs), (iii) Operations in security constrained settings.

Moreover, there is a procedure proposed for the import and export of conceptual graph files into RDF files. Besides, there is a recent procedure proposed for the conversion of the EXPRESS schema of IFC into an OWL ontology that supports the conversion of IFC files into equivalent RDF graphs (Pauwels and Terkaj, 2016; Pauwels, 2017). As a result, the generated RDF graph representation for the IFC files can easily be formalized with visual reasoning in the conceptual graphs environment (see Figure 3). There are also visual editors available for semantic web technologies, (e.g. Topbraid) with the possibility of using both logical and graphical reasoning.

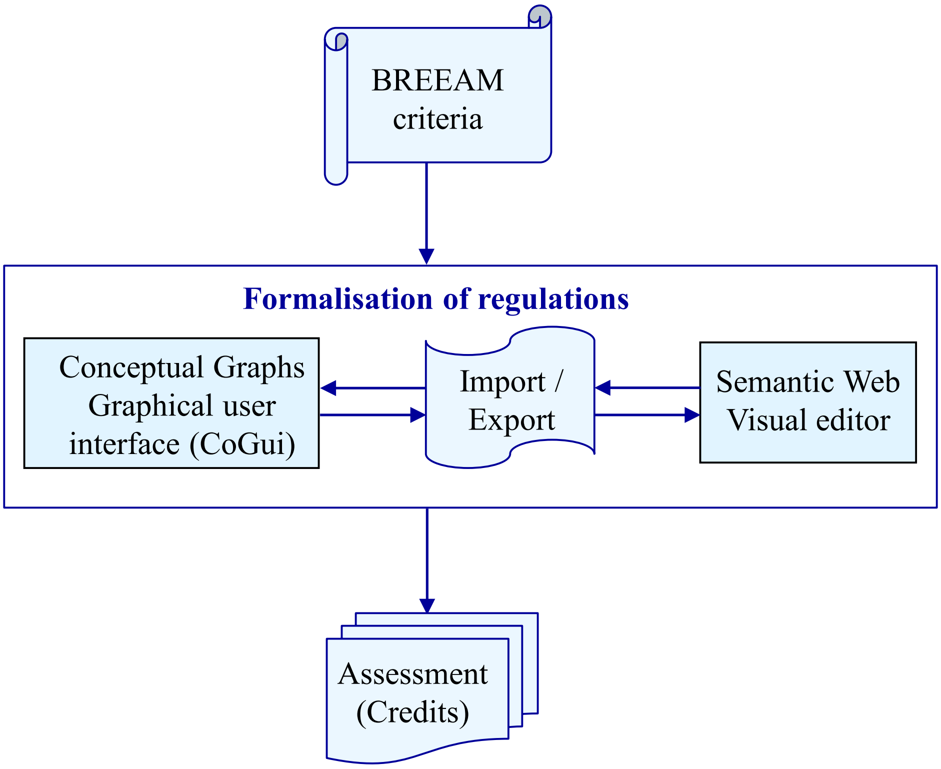

Figure 3: Implementation process into CoGui

Based on Figure 3, various screenshots (e.g. Figure 4) generated from the CoGui editor will be discussed.

3.4.1 Ontological knowledge with concept and relation types

Based on the definition of the terms in BREEAM (BRE Global Ltd, 2015), concepts or classes with their respective sub-concepts were abstracted and modelled in Conceptual Graphs Graphical user interface (CoGui) as depicted in Figure 4.

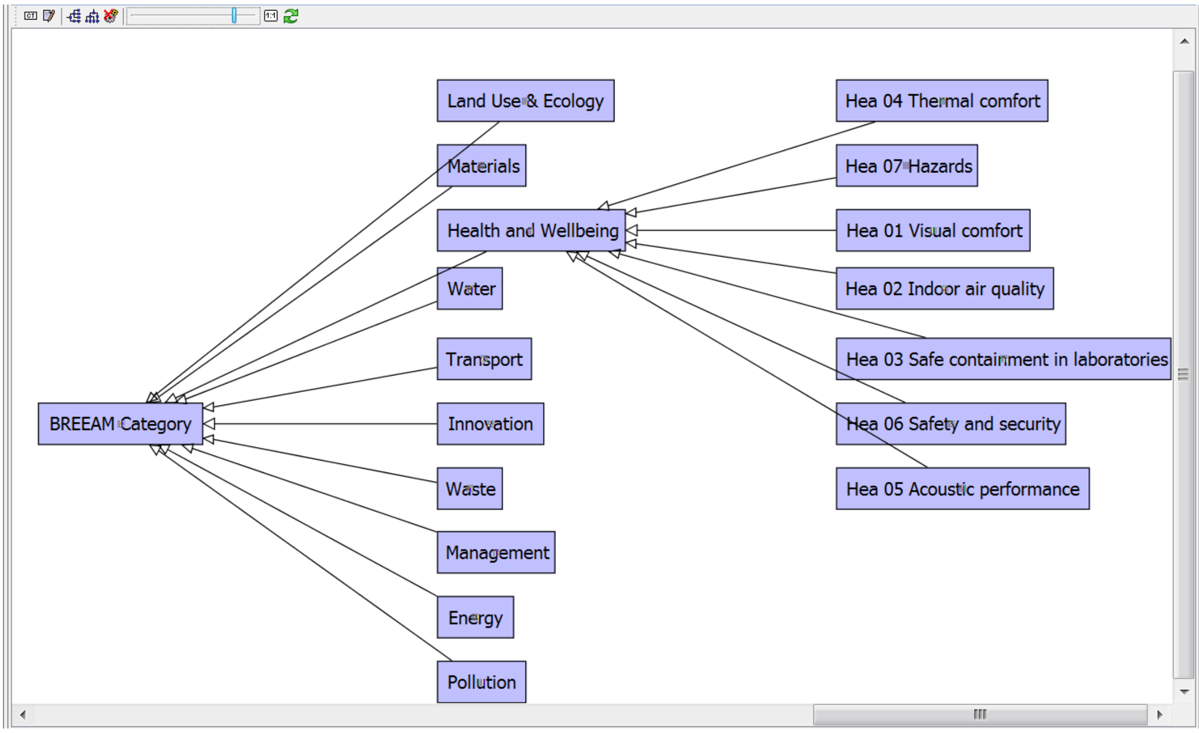

Figure 4: BREEAM categories in a parent-child 'is-a' relationship tree.

Based on Figure 4, the first levels of BREEAM sections are Management, Health and Wellbeing, Energy and Transport. There are subsections underneath other sections. For instance, the following sub-sections are subsections underneath the Health & Well-being: Visual comfort, Indoor air quality, Safe containment in laboratories, Thermal comfort, Acoustic performance and Safety and security. The following sub-sections are underneath the Pollution: Impact of refrigerants, NOx emissions from heating source, Surface water run-off, Reduction of night time light pollution and Noise attenuation.

Some relations may be established between the concepts and used for the modelling of factual and inferential knowledge in conceptual graphs. This can facilitate automated reasoning in experience feedback processes. Figure 5 depicts the relationships (Comparison operators and Usual relations) between concepts and their sub-relationships.

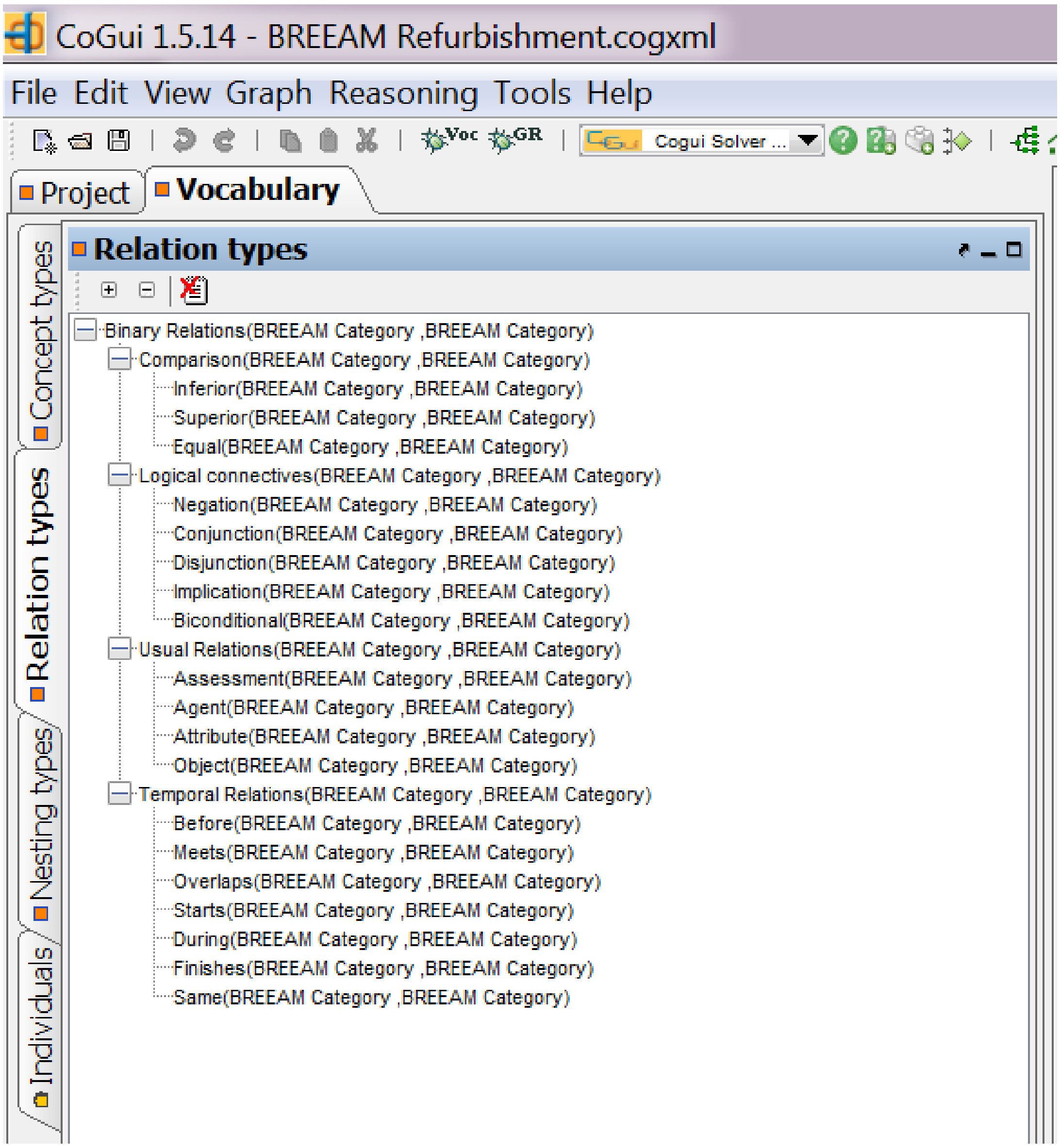

Figure 5: Relation types in a subPropertyOf hierarchy

The relations in the tree are defined according to common relational operators (comparison, and logical operators), usual relations and possible temporal relations specified in Allen's Interval Algebra (Allen, 1983). Comparison operators (Equal, Inferior and Superior) can be used to compare two concepts with the logical true and false results. Usual relations (such as Element, Assessment, Agent, Attribute and Object) refer to the construction of sentences in terms of subject, verb and object in the common language with active and passive components. The concept type hierarchy has been modelled based on the BREEAM manual. The hierarchical representation is not exhaustive. There can be other links between any two concepts. For example, the relation type "agent" suggests a thematic relation that refers to the cause or initiator of an event. For instance, the concept "Energy" is an agent of the BREEAM requirements. A more restrictive management of signatures concerning relations can be put in place when it is necessary to restrict the lists of concepts involved in a particular type of links that characterize a conceptual relation.

3.4.2. Factual knowledge encoded by conceptual graphs

Conceptual graphs were introduced by Sowa as a diagrammatic system of logic with the purpose "to express meaning in a form that is logically precise, human readable and computationally tractable" (Sowa, 1976). Conceptual graphs encode knowledge as graphs and can thus be visualized in a natural way (Sowa, 2000):

- The specification of conceptual definitions, which can be seen as a basic ontology, is made of concepts and relations with the possibility of implementing multiple inheritance;
- All other kinds of knowledge are based on the representation of concepts and their relationships. This representation is encoded by a labelled graph, with two kinds of nodes, respectively corresponding to concepts and relations. Edges link a concept node to a relation node;

A conceptual graph G can be considered as a bipartite multi-graph, defined on an ontology V. Let V=(Tc, Tr, I) where Tc is the hierarchy of concept types, Tr the hierarchy of relation types and I the set of individual markers. Defined on V, G is made of two disjoint sets of nodes such that any edge joins two nodes of each of the sets: the set of concept nodes (C) included in Tc and the set of relation nodes (R) included in Tr. According to (Chein and Mugnier, 2009), G is a quadruplet G=(C, R, E, L) satisfying the following conditions:

- C and R are the node sets, respectively, of concepts nodes and of relations nodes.
- E is the multi-set of edges. Edges incident to a relation node are totally ordered.
- L is the labelling function of G's nodes satisfying:
    a. A concept node c is labelled by a pair (type (c), marker (c)) where type (c) belongs to Tc and marker (c) belongs to I $\cup$ {*}. * is the generic marker unlike others that are individual markers.
    b. A relation node r is labelled by L (r) and belongs to Tr. L (r) = (type of r) = type (r)
    c. The degree of a relation node r is equal to the arity of the type of r
    d. The incident edges at r are completely ordered and labelled from 1 to arity (Type (r)).

3.4.3. Inferential knowledge encoded by graph rules

A rule expresses implicit knowledge of the form: "if the hypothesis, then the conclusion", where the hypothesis and conclusion are both basic graphs. Using such a rule consists of adding to the conclusion graph (to some fact) when the hypothesis graph is present (Mugnier et al., 2012). There is a one-to-one correspondence between some concept nodes of the hypothesis with concept nodes of the conclusion. Two nodes in correspondence refer to the same concept. These nodes are said to be connection nodes. The knowledge encoded in rules can be made explicit by applying the rules to specified facts.

Beyond the production of new knowledge, automatic reasoning allows us to query knowledge base expressed in Conceptual graphs. The query's graph asks a specific question concerning the facts included in the knowledge base. An answer can be given to this question thanks to conceptual graph homomorphism mechanism (called *projection*) which consists in establishing a correspondence between the vertices of the query graph and those of another (in particular a fact) that may contain the answer (Mugnier, 1995). A homomorphism h from a conceptual graph H to a conceptual graph G is an application which associates to each node of H a node of G more specific or equal to the node of H (Baget and Mugnier, 2002). More simply, it is a match for all nodes H to all nodes in G that preserves the specialization relations of the ontology. This relation is equivalent to the fact that H is a generalization of G. We say that H subsumes G if and only if H is a generalization of G. A symbolic illustration of projection is presented in Figure 6.

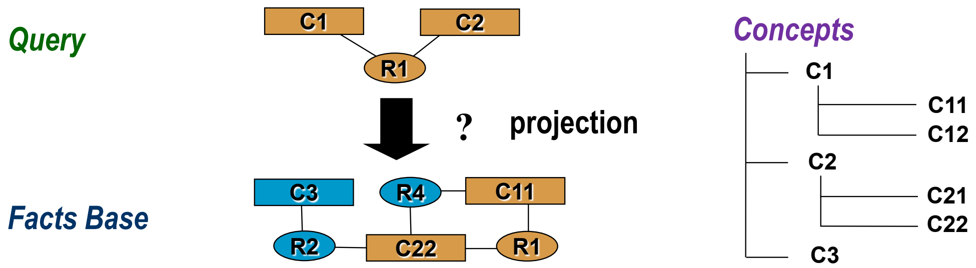

Figure 6: Projection operation for information retrieval

In the conceptual graphs, when they refer to the same entity, it is necessary to specify that concepts are coreferent (i.e. they have the same referent). This is done in the conceptual graph rule, with the pairs of vertices determining the link between the hypothesis and the conclusion of the rule. Figure 7 represents the modelling of an associated rule in the conceptual graph formalism concerning the *Sustainable procurement*. *Sustainable procurement* is a concept obtained from BREEAM.

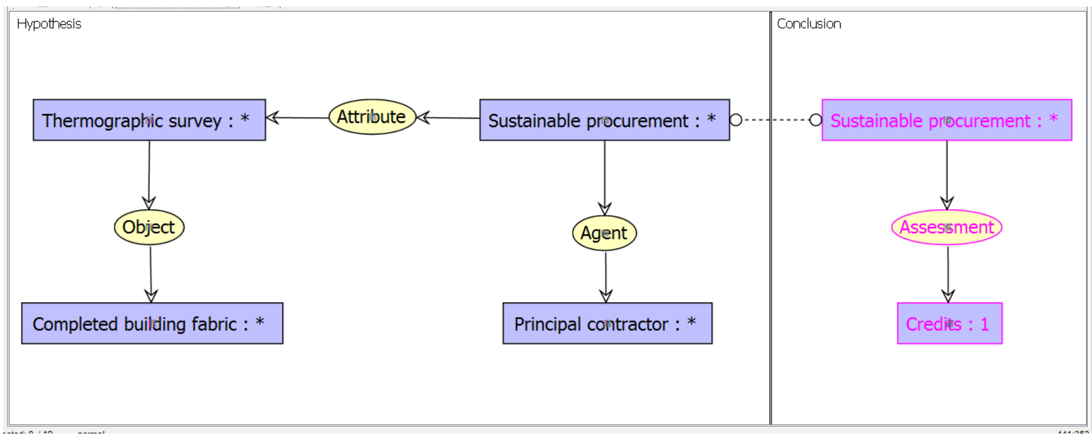

Figure 7: A rule modelling a sustainable procurement assessment

The rule in Figure 7 means, if a *Principal contractor* carries out a *Thermographic survey* of the *Completed building fabric*, then the assessment of the *Sustainable procurement* should be one BREEAM credit. The logical representation of the preceding statement is articulated in the ensuing rule.

Logical expression: *∃x ∃y ∃z ∃t (Sustainable procurement (x) ∧ Thermographic survey (y) ∧ Completed Building fabric (z) ∧ Principal Contractor (t) ∧ Agent (x, t) ∧ Attribute (x, y) ∧ Object (y, z)) → (Sustainable procurement (x) ∧ Credit (1) ∧ Assessment (x, 1))*

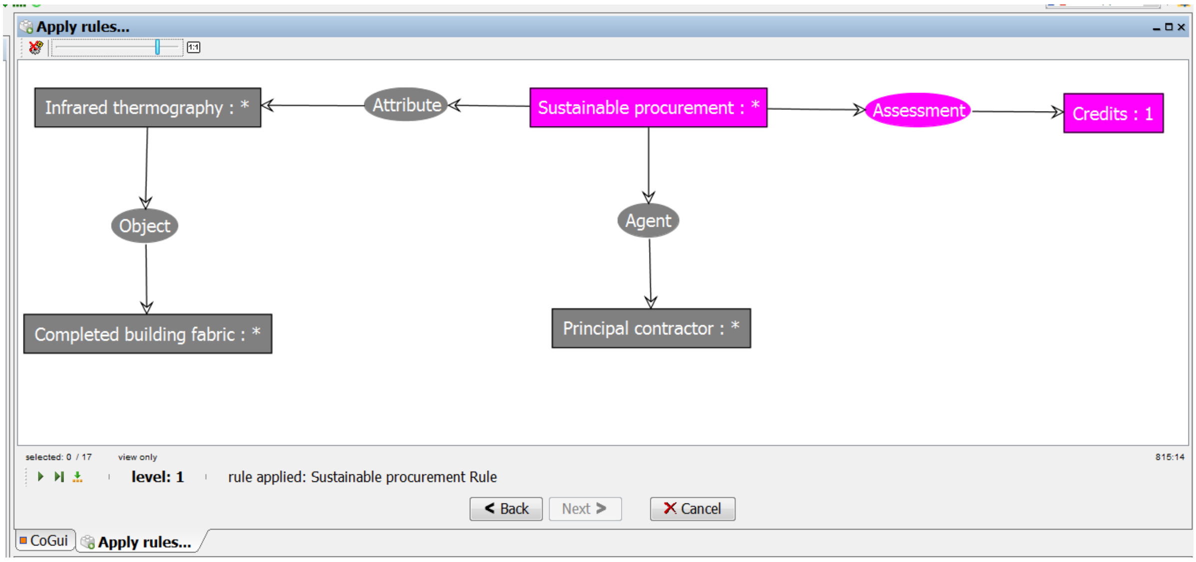

Figure 8: A compliance checking with the rule of sustainable procurement

A *thermographic survey* (also called *thermal imaging survey*) is employed as a way of producing images and showing the heat distribution over the surface of a building envelope. *Thermographic surveys* can be carried out in accordance with documented methodologies such as: *thermal performance of buildings*, *qualitative detection of thermal irregularities in building envelopes* or *Infrared thermography*. So, an *infrared thermography* is defined as a subClassOf *thermographic survey*, which in turn is a super type of the concept *infrared thermography*. Figure 8 reveals whether a building project in which sustainable procurement has as attribute *infrared thermography* meets the specified BREEAM requirements. Consequently, in Figure 8, there is a match between facts and rules because *thermographic survey* matches (by conceptual specialisation) with "*infrared thermography*". Concretely, in conceptual graph theoretical terms, there is a projection from the graphical specification of *sustainable procurement* rule via *thermographic survey* concept to the conceptual graph fact for a target building model of *sustainable procurement* with *infrared thermography*. In this case, there is compliance with the BREEAM standard.

Figure 9 represents the modelling of an associated rule in the conceptual graph formalism concerning the *Energy monitoring*. The rule in Figure 9 means, if there is a provision to provide a *Building Energy Management System* (BEMS) to monitor the major energy-consuming services then the assessment of the *Energy monitoring* should be one BREEAM credit.

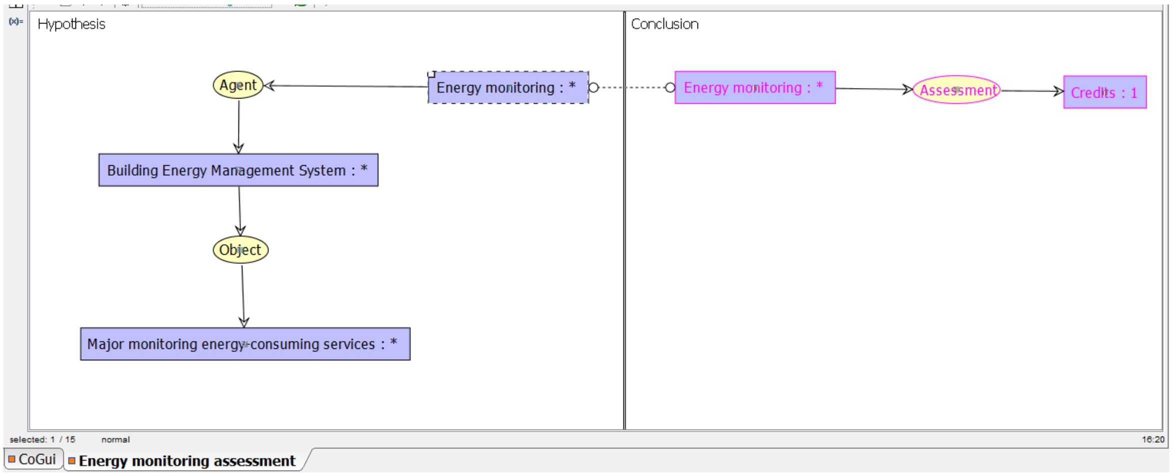

Figure 9: A rule modelling an Energy monitoring assessment

Logical expression: *∃x ∃y ∃z (Energy monitoring (x) ∧ BEMS (y) ∧ Major monitoring energy-consuming services (z) ∧ Agent (x, y) ∧ Object(y, z)) → (Energy monitoring (x) ∧ Credit (1) ∧ Assessment (x, 1))*

Figure 10 reveals whether a building project in which *Energy monitoring* has as object *Major monitoring energy-consuming services* meets the specified BREEAM requirements. Concretely, in conceptual graph theoretical terms, there is no projection from the graphical specification of Energy monitoring rule with *Major monitoring energy-consuming services* concept to the conceptual graph fact for a target building model of Energy monitoring with *Minor monitoring energy-consuming services* concept. In this case, there is no compliance with the BREEAM standard.

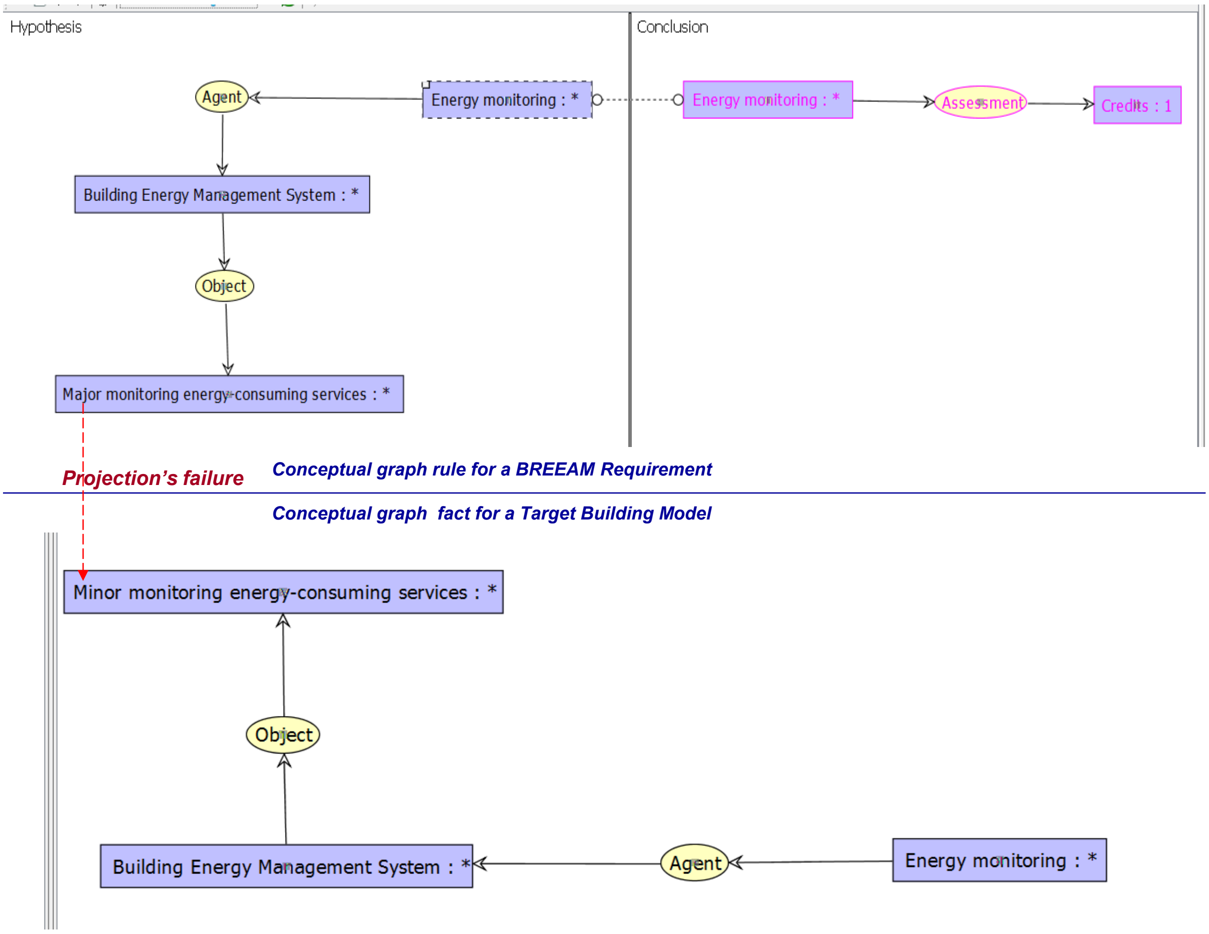

Figure 10: A compliance checking with the rule of energy monitoring

4. Formalisation of BREEAM requirements using conceptual graph rules

4.1. The illustration of a country's reference sheet- France

As an organisation, BREEAM International encourages the use of local best practice codes and standards in the country where they were developed. Country reference sheets (i.e. reference record containing national best practice standards in the country) are obtainable for each country highlighting where diverse requirements or various standards should apply. All codes and standards listed in country reference sheets have been confirmed by BREEAM International as appropriate standards which can be used to establish compliance for the issues which are under assessment.

Credit number	Reference in BREEAM Manual	Issues covered by the local best practice standard/guide/tool	European Standard reference	Local standard/tool reference
Man 04	**Commissioning code for Heating systems**	Pre-commissioning checks (e.g. state of the system, water tightness and pressure test, system filling and	CEN EN 14336:2004 Heating systems in buildings. Installation and	Construction functional tests and commissioning

		cleaning, system filling and venting, frost precautions, mechanical and electrical checks)	commissioning of water based heating systems	tests: This is the final verification before receipt, carried out by the company on its equipment to ensure their proper operation under normal conditions of use. The equipment concerned is the electrical installations of housing or general services, the water networks inside the buildings, the evacuations of water inside and outside the buildings, the electronic door openers, the Controlled Mechanical Ventilation (single-flow system).
		Setting to work (e.g. initial run)		
		Balancing water flow rates and tolerances		
		Adjusting controls (actuating units, transmitters, sequence control and plant operation)		
		Reporting and documentation (e.g. proformas, completion certificate)		

Table 5: An excerpt of the information displayed in the country reference sheet - France

Table 5 shows an excerpt (concerning *Commissioning code for heating systems*) of the information displayed in the country reference sheet for France. This information is related to the BREEAM concept called "*Man 04 Commissioning and handover*". The aim of "*Man 04 Commissioning and handover*" is to encourage a properly planned handover and commissioning process that reflects the needs of the building occupants. This concept is split into four parts:

- Commissioning and testing schedule and responsibilities (1 credit)
- Commissioning building services (1 credit)
- Testing and inspecting building fabric (1 credit)
- Handover (1 credit).

The semantic modelling process of BREEAM requirements can use an intermediate representation from which a formal visualization in the conceptual graph rule is generated. This reflects a more general approach in the progressive structuring of a description of properties characterizing the knowledge elements that are useful for regulatory or compliance requirements. These requirements are specific to a target domain and can be given by experts in natural language or described in various formats (e.g. best practices, local codes and standards, normative documents). This intermediate representation can be constructed on a logical basis taking into account the structure of the natural language. For instance, the BREEAM requirement can be described with an intermediate representation characterized by a triplet (H, R, C) composed of a Hypothesis H, a causal relation R and a conclusion C (see Table 6).

BREEAM section: Management (Man 04 Commissioning and handover)		
The aim is to encourage a properly planned handover and commissioning process that reflects the needs of the building occupants.		
Hypothesis	***Relation***	***Conclusion***
– Commissioning - testing schedule and responsibilities – Commissioning - design and preparation – Testing and inspecting building fabric – Handover	- Implication	– The reference in BREEAM manual is Commissioning and handover which is associated to 4 credits.

<u>Table 6</u>: the intermediate representation of a BREEAM requirement with a triplet (H, R, C)

Figure 11 represents the modelling of an associated rule in the conceptual graph formalism concerning the management concept *Man 04 Commissioning and handover* having 4 credits available in the assessment criteria.

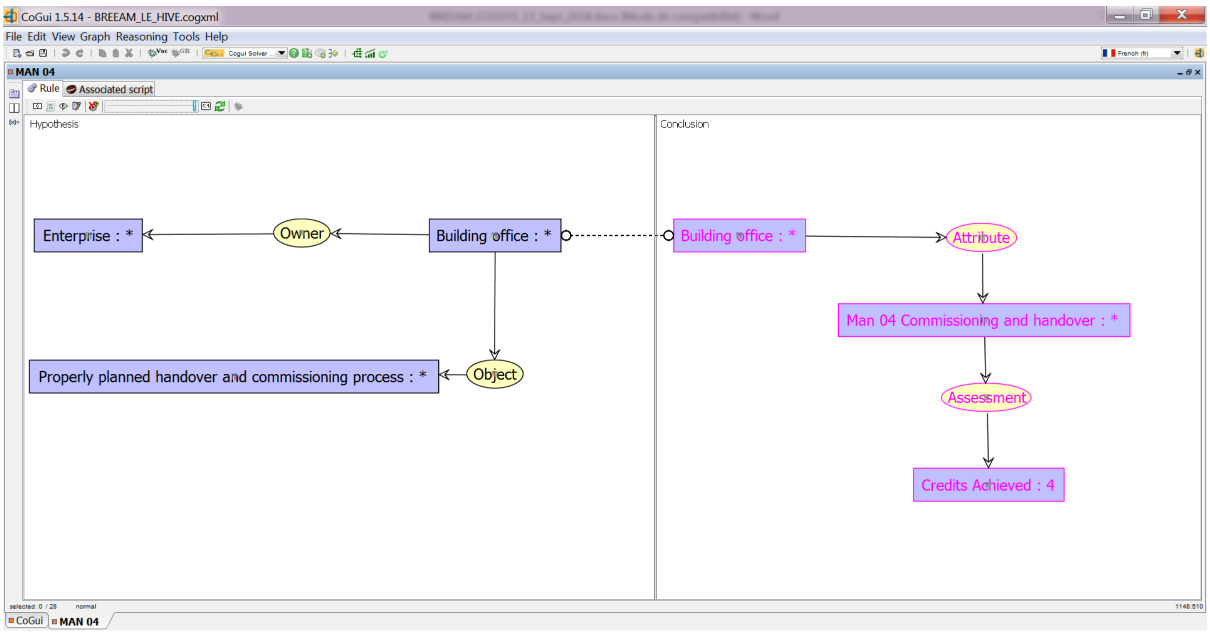

Figure 11: A rule modelling Man 04 Commissioning and handover

The corresponding logical expression for Figure 11 is presented below.

Logical expression*: ∃ x ∃ y ∃ z Enterprise (x) ∧ Building office (y) ∧ Properly planned handover and commissioning process (y) ∧ Owner (x, y) ∧ Object (y, z) → Building office (y) ∧ Man 04 Commissioning and handover (y, z) ∧ Credits Achieved (4) ∧ Attribute (y, z) ∧ Assessment (z, 4))*

There are other commissioning codes that can be checked by similarly undertaking formal modelling with conceptual graph rules. The following commissioning codes can also be considered:

- Commissioning code for water distribution systems:
  - Design for commissionability requirements (clear schematics in line with specifications, electrical safety, etc.)
  - Pre-commissioning (e.g. state of the system, mechanical and electrical checks)
  - Illuminance levels of internal, emergency and external lighting
  - Lighting controls (e.g. daylight and occupancy sensors, override controls, end-user operated systems, Building management system (BMS))
  - Reporting and documentation (e.g. proformas, completion certificate)
- Commissioning code for ventilation systems:
  - Pre-commissioning (e.g. schematics in line with specifications, state of the system, air regulating devices, fan and electrical checks)
  - Setting to work (e.g. test run, adjustment of controls and components)
  - Functional measurements (e.g. regulation of air flow, variable air volume systems, pressure regimes)
  - Measuring methods and measuring devices (e.g. flow rates and tolerances)
  - Reporting and documentation (e.g. proformas, completion certificate)
- Commissioning code for refrigeration systems:
  - Design for commissionalility requirements (clear schematics in line with specifications, system design, tolerances, etc.
  - Pre-commissionning (e.g. state of the system, mechanical and electrical checks)
  - Combined pressure and leak testing (methods and procedures)
  - Evacuation and dehydration methods
  - Setting to work and adjusting (e.g. system checks, start-up, shut-down, running-in)
  - Test apparatus and instruments
- Commissioning code for lighting systems
  - Design for commissionability requirements (clear schematics in line with specifications, electrical safety, etc.)
  - Pre-commissioning (e.g. state of the system, mechanical and electrical checks)
  - Illuminance levels of internal, emergency and external lighting
  - Lighting controls (e.g. daylight and occupancy sensors, override controls, end-user operated systems, BMS)
  - Reporting and documentation (e.g. proformas, completion certificate)
- Commissioning code for automatic controls:
  - Design for commissionability requirements (e.g. control system specification details, sensors, control valves, access, etc.)
  - Pre-commissioning (e.g. control application software, control panels, wiring, field control devices, etc.)
  - Control strategy checking (e.g. time schedules, control loops, sequencing, start-up and shut-down)

    - Checking procedures for basic control functions (e.g. optimiser, compensation, control of natural ventilation).
    - Lighting controls (daylight, occupancy sensors)
    - Occupant interfaces
    - Integrated systems
    - Security systems
    - Reporting and documentation (e.g. proformas, Operations and Maintenance (O&M) manual, completion certificate)

4.2. Case study with the "Le Hive" Offices in Paris, France

A case study application will now be used to illustrate the application of BREEAM rules. The case study is the "Le Hive offices" in Paris, France. This case study has used BREEAM to continuously drive improvement in its sustainable use of offices in the Paris area, specifically the French Schneider Electric's global headquarters, which has been noted as the hall of innovation and energy showcase. The building offers many services for employees, such as rest lounges, a fitness centre, an electrical car service and family days. Energy use for Heating Ventilation and Air Conditioning (HVAC) and lighting has been halved in three years through active energy efficiency. According to Schneider's business strategy, the use of BREEAM in "Le Hive" is underpinned by the following aspects:

Management:
- building management team focussed on energy efficiency and occupiers comfort
- empowerment and awareness of the occupiers (e-learning, sustainability events, etc.)
- high quality of the building maintenance (facility management)
- equipment and process security and safety for the occupier and the building.

Materials:
- use of sustainable materials with a minimum of pollutants
- purchase of sustainable and low consumption services and products.

Transport:
- actions and equipment facilitating low carbon means of travel– electric vehicles, bicycle parking and tracks, carpooling, transport plans, etc.

Waste:
- recycling and sorting of 12 kinds of waste (0% to landfill).

Water:
- efficient management of water – rain sensors, real time leak detection, etc.

Health and well-being:
- services on site such as like fitness facilities, laundry, hairdressers and car washes
- consultation with occupiers
- acoustic comfort improvement
- innovative comfort measurement.

Pollution:
- greenhouse gas emissions study
- use of 100% eco-labelled products for cleaning.

Energy:
- closely managed energy consumption with a dedicated manager for energy and the environment, and centralized control and monitoring using innovative tools.

Landscape and ecology:

- conservation of green areas, improvement of biodiversity, establishment of beehives on site.

In this context, the Building Management Systems (BMS) plays a decisive role, since it allows us to control and monitor HVAC, lighting, fire and security systems with the example of an Air Handling Unit shown in Figure 12. Other success factors include real-time monitoring of consumption for improved eco-performance, optimization of the building's occupancy rate, involvement of the building's residents and a location at the heart of an intelligent ecosystem.

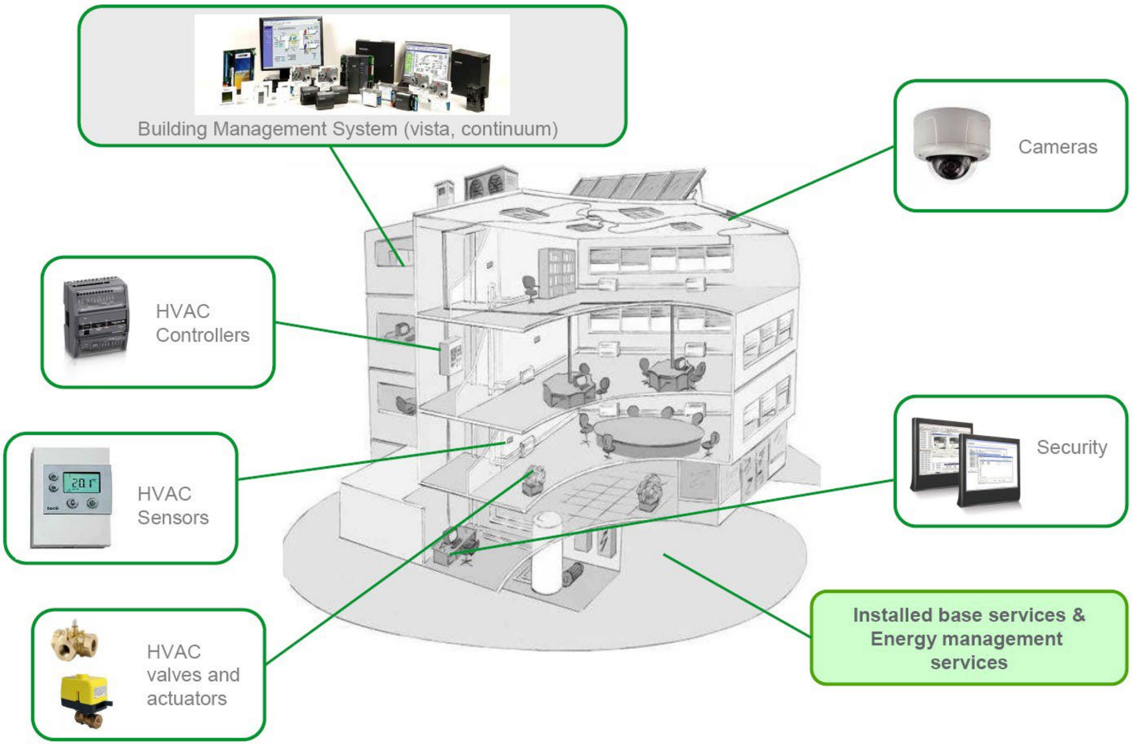

Figure 12: Building Management Systems (BMS) of the HIVE

The “Le Hive” was the first international building to be certified “Outstanding” (6 stars) for building management performance (see Table 7). This new certification goes beyond energy-efficient solutions (energy, water and waste management) implemented in the building, as it also focuses on key indicators such as:

- Employee satisfaction and well-being (on-site services and events, satisfaction surveys, improved acoustics)
- Employee education and engagement
- Sustainable management of the building’s environment: preservation of green spaces and biodiversity (bee hives installed)
- Focus on CO_2 neutral transportation, proximity to public transportation, electric vehicles available for use by employees, photovoltaic charging stations, enlargement of the bike parking lot, car sharing incentive programs through investment in the development of a specific website for people living and working in the neighbourhood of the site.

BREEAM Section	**Credits Achieved**	**Credits Available**	**% of Credits Achieved**
Management	21	21	100%
Health and Wellbeing	20,46	22	93%
Energy	21,7	31	70%
Water	8,5	10	85%
Materials	14	14	100%
Land Use and Ecology	10	10	100%
Pollution	11,7	13	90%
Final BREEAM score			**88%**
BREEAM Rating			***Outstanding***

Table 7: BREEAM Rating (Le HIVE): Building management performance

Each BREEAM concept puts its focus on an aspect of the assessment procedure. For instance, "Management" encourages the adoption of sustainable management practices in connection with design, construction, commissioning, handover and aftercare. Categories in this concept with available and achieved credits by the Le Hive case study are detailed in Table 8.

Management Category	**Description**	**Credits Achieved**	**Credits Available**
Man 01 Project brief and design	Encouraging an integrated design process to influence decision-making and optimise building performance.	4	4
Man 02 Life cycle cost and service life planning	- Promoting the business case for sustainable buildings. - Improving design, specification, maintenance and operations.	4	4
Man 03 Responsible construction practices	- Encouraging construction sites to be managed in an environmentally and socially considerate and responsible manner. - Monitoring encourages continuous improvements and utility consumption reduction.	6	6
Man 04 Commissioning and handover	- Encouraging a well-managed handover and commissioning process. - The building responds to the needs of the occupants.	4	4
Man 05 Aftercare	- Encouraging aftercare support during the first year of the building operation.	3	3

Table 8: BREEAM Rating with "Management" of the "Le HIVE"

The conceptual graph rules describing the categories included in the BREEAM Rating with "Management" of the "Le HIVE" are described in figure 13.

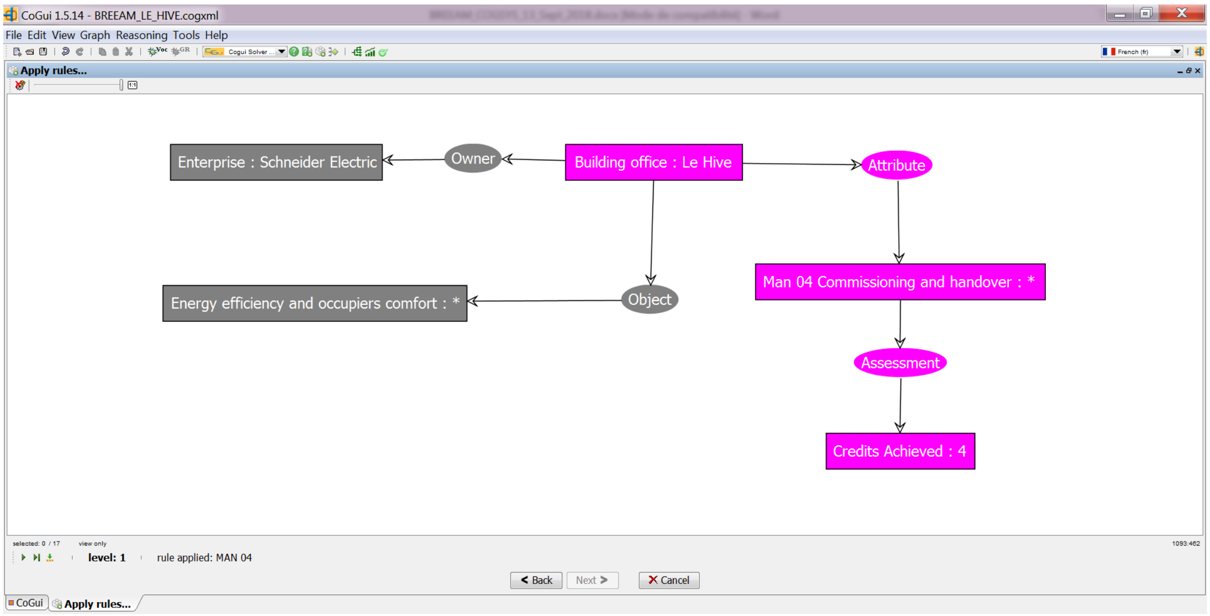

Figure 13: Conceptual graph rule application for BREEAM Rating of the “Le HIVE”

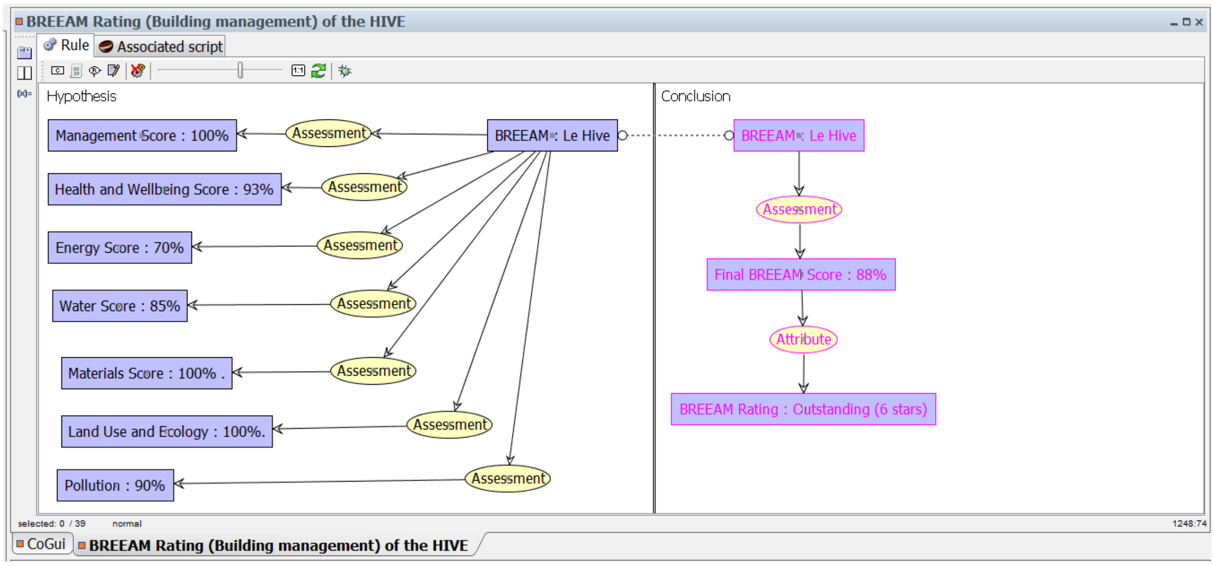

Figure 14: Conceptual graphs for the BREEAM Rating (Building management) of the HIVE

In Figure 14, a synthetic view of a conceptual graph describing the conclusion inferred by applying the BREEAM encoded rules on the description of the information acquired from the Le Hive is presented. For the BREEAM Rating (building management performance) of Le Hive, different BREEAM Sections (Energy, Water, Materials, Materials, Land Use & Ecology, Health & Wellbeing and Management) are discussed and assessed according to the BREEAM encoded rules. The values (also called individual markers) are explicitly included in the rules described in conceptual graphs (see Figures 13 and 14), but these graphs can be used in different projects by replacing the displayed values by those specific to the target project to be assessed. The set of individual markers are disjoint from the set of concept and relation types and this will ensure that the information can be easily updated by the involved assessor. For the assessor, it is possible to simply use a tabular form with all the statements describing the BREEAM assessment. The conceptual graphs representation with an underlying logical semantics can be exploited, since the associated semantics checking is useful to reduce inconsistencies and incompleteness in built knowledge base. There may still be uncertainties related to the lack of precision and explicitness, for example from tacit obvious information or incomplete facts. Indeed, it is imperative to have tools with graphical user interfaces (GUIs), either on top of conceptual graphs or semantic graphs.

5. Discussion and Conclusion

In this study, a formalization of the construction domain knowledge is based on the principles of conceptual graphs to check efficient satisfaction of model constraints for sustainable development processes. From the early design stage of a project, the principles encompassed within the suggested framework enable automatically checking the rules of the BREEAM sustainability standard. The proposed graph-based approach for knowledge reasoning facilitates the compliance checking of rules that the designer has established (bioclimatic performance, comparison of construction methods, overall costs on the envelope, footprint). The approach adopted in this study focuses on the verification of rules and constraints related to BREEAM assessment of construction projects based on the knowledge representation and reasoning using conceptual graphs. The case study concerns the deployment of the proposed methodology for the formal analysis of the BREEAM assessment of the building called "Le HIVE" that has been certified as an "Outstanding" for BREEAM rated building. This case study is regarded as helpful for identifying the factors that lead to sustainable buildings. Consequently, in accordance with the national thermal regulations, significant energy savings can be made during the use of the buildings. The factors contributing to the possible achievement of results include improvements of the building (optimization of equipment and operations, reduced energy consumption and decreased environmental impact), and to the comfort levels (e.g. light, temperature, direct sunlight, acoustic insulation, etc.) appreciated by the building's occupants. From perspectives of information processing, the encoded formats can be read by other knowledge modelling tools such as CoGui that can read and output rules. So the developed reasoning can be exploited by different building domain actors working with their preferred tools for domain modelling (ontology representation) and inference mechanisms (rule engines). For instance, the BREEAM file is converted into a CoGui format and represented by graph rules also in CoGui format. Therefore, it is possible to work in two modes: (i) internal mode by using the visual reasoning operations of conceptual graphs in CoGui; (ii) external mode by exporting the CoGui resulted file into RDF format in order to allow it to be read by other knowledge engineering tools such as Protégé. This operation facilitates the semantic interoperability for correct exchange of information between various software tools that can be employed by several remote collaborative actors.

The proposed approach for compliance checking is focusing on the conceptual graphs with the possibility of using semantic web technologies. The existence of a translation between RDF and conceptual graphs is useful for both conceptual graphs and semantic web technologies:

- For the conceptual graph tools there is a noticeable interoperability advantage (adhering to an established standard). One value of this advantage is the fact that many of RDF(S) tools and software libraries are available, therefore equipped for use in the situation of testing conceptual graphs algorithms to provide more modern and optimized solutions.

- For the Semantic Web tools, the conceptual graph-based visual tool, offers the possibility of using any of both options for knowledge representation and reasoning in the same software depending on the various cognitive considerations. Lastly, the RDF researchers might take advantage of the existing philosophies (e.g. geometric intuition invoked for reasoning) underlying conceptual graph operations for possible extensions and alternative services.

Generally, the definitions of an ontology must be evolved incrementally over time to ensure a continued response to regular update requirements. In this case, the current ontology description for BREEAM assessment can be expanded incrementally over time as specific needs and opportunities are identified, rather than as part of a static descriptive ontology thought out in advance. Besides, in conceptual graphs, an assumption that any pair of concepts having different individual instances refer to different entities in the world are made. This guarantees the uniqueness of identifiers for concepts with individual markers. The terminological ontology (concept and relations types of BREEAM) can be specialised (by adding specific concept and relations types) and instantiated (by adding individual markers) according to the factual knowledge. Hence, the rules will be much more explicit, using terms from a closed and restricted (by specialisation and instantiation) terminological ontology, which is aligned with BREEAM and the factual knowledge. In that sense, one can consider some well-known aspects of the BREEAM regulations that are closer to the information in the building model (e.g. energy performance or thermal insulation checking).

A growing number of construction and public works companies are now implementing BIM in their projects. Digital building information models are intelligent and facilitate efficient collaboration, sharing of construction information and delivery of projects. BIM also facilitates the understanding of the technical processes, the construction modes as well as the costs of a building site through a 3D interface. In future work, particular attention will be given to the steps of manipulating the reasoning operations of rule-processing engines with ontology-based approaches in BIM. It can be appropriate to consider more elaborate reasoning processes that involve manipulating a rule-processing engine with composition of inference rule-sets (Belsky et al., 2016). So, the development of ontology technology in the area of BIM semantic-enrichment is relevant for the management of complex knowledge related to non-geometrical features (Simeone et al., 2019).

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