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CLASSIFICATION OF BIM-BASED MODEL CHECKING CONCEPTS

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SUMMARY*: This paper proposes a framework for classification of Building Information Model (BIM) checking concepts. Although BIM-based model checking (BMC) and similar terms are widely used, there is a lack of joint understanding of the different types of checking and the use of terms. The study uses an ontological approach to develop a framework with the intention to classify unique concepts of BMC. The following concepts for BMC were identified: A) Compliance checking solutions, separated into: 1) Validation checking and 2) Content checking, and B) Design solution checking, separated into: 3) Smart objects checking and 4) Design option checking. All concepts are presented with principles and examples, and as Linked Data with RDF-graph. The impact of this overview can contribute to improved understanding of BMC, improved understanding and clarification of expectations, and joint terms for common use.*

KEYWORDS*: BIM-based model checking, ontology, classification, taxonomy, Linked Data*

REFERENCE: *Eilif Hjelseth (2016). Classification of BIM-based model checking concepts. Journal of Information Technology in Construction (ITcon), Special issue: CIB W78 2015 Special track on Compliance Checking, Vol. 21, pg. 354-369, http://www.itcon.org/2016/23*

1. INTRODUCTION

The importance of precise use of terms for joint understanding is indisputable. It is hard to see a coherent use of terms within BIM-based model checking (BMC). BMC consists of two related parts: an information source (BIM) and algorithms for processing this information (rules). A result of this split is that specification of rules can be traded as a commercial service.

A search for related terms resulted in the following list: Compliance checking, Code compliance checking, Clash detection, Rule checking, Model checking, Validation checking, BIM-checking, Quality checking and many more. The ISO Concept Database (ISO, 2016) does not contain any of the terms above. It would therefore be useful to have a system for classification of different types of BMC. This paper intends to improve this situation by presenting a classification of different types of BMC and their related terms.

Often the type of model checking can be understood by the context, while at other times this is so wide that it includes everything related to some type of checking. The lack of joint use of terms for BMC makes it very hard to assess the contribution of an article without reading it from start to finish to discover what "type" of checking was involved, and what the benefit was for the users. Understanding BMC as clash detection is in principle not wrong, but it is a very limited perspective. Clash detection for building parts and rule checking of regulations seem to be the dominant understandings. Clash detection represents a relatively simple way of checking the model. Rule checking of codes represents the opposite position, where many rules must be used to perform one validation of a solution in the BIM. Regarding understanding of checking, we see that BMC related terms are used in an inconsistent way, and with varying expectations and experiences.

BMC is expected by McGraw-Hill (2014) to be one of the major contributions to utilisation of BIM in the industry. BMC is often identified by the use of one particular type of software. There is also a relatively limited number of developers and vendors such as Solibri Model Checker, Autodesk Navisworks, or Tekla BIMinsight (Hjelseth, 2015). The situation for public services for compliance checking of building permit applications is characterized by high expectations, but low rate of implementation. Norway and Singapore are listed on top regarding digital solutions for building permit applications (Refvik, 2013). An overview of concepts for BMC can contribute to increased development of different types of BMC, adapted to different purposes in the life cycle of the building.

The complexity in the design, construction and facility management process is increasing. According to Ingvaldsen, (1994, 2001) as much as 40% of defects may be related to blunders in the design process. Although these studies are from some years back, it is not likely that errors in the design process have decreased. A study by Lopez & Love (2011) about design error costs in construction projects reported that the mean direct cost was 6.85% and indirect costs were 7.36% relative to contract value. Increasing complexity of solutions in the built environment should require increased support of BMC – not only clash detection. An overview of concepts for BMC can contribute to increased awareness of different types of rules, how these support different purposes, and how these can be implemented into BMC related solutions.

There is need both for understanding the different types of BMC concepts and for labelling them with joint terms. The research question is: "*How can different concepts of BIM-based model checking (BMC) be defined?*".

2. METHOD

This study takes an analytical approach based on ontology by using pre-defined characteristics to classify different groups and types of BMC. Simply speaking ontology focuses on "what things are", and not what they are called. According to Gruber (1993), this can be expressed as: "An ontology is an explicit specification of conceptualizations, used to help programs and humans share knowledge". Model checking can be regarded as a part of a knowledge system. This knowledge perspective is also supported by Hendler et al. (2000) who practically equates ontology with knowledge base.

Taxonomy can be expressed as the process or system of describing the way in which different things are related by putting them in groups (Merriam-Webster, 2016b). Furthermore, classification can be expressed as the act or process of putting people or things into groups based on ways in which they are alike (Merriam-Webster, 2016a). Taxonomy acts as a scheme or rule for classification by specifying distinguishing characteristics for grouping into distinct classes. Classes can be described in terms of necessary and sufficient conditions. According to Newell (1982), we use common ontologies to describe ontological commitments for a set of agents so that they can communicate about a domain of discourse without necessarily operating on a globally shared theory. We say that an agent commits to an ontology if its observable actions are consistent with the definitions in the ontology. The idea of ontological commitments is based on the Knowledge-Level perspective (op. cit.). This perspective indicates that BMC should be regarded as an element in a continued processing of embedded knowledge into computable solutions for automatic and semi-automatic processing. This implies that specification of rules can be defined as a separate service. Such a top-down approach for defining concepts for BMC is based on following a predefined set of characteristics: Structure of information, Information requirement, Structure of rule, Logic in rule, Outcome. This structure is the foundation for organizing the Resource Description Framework (RDF) triples and, after RDF/XML serialisation, presenting this as an RDF-graph. The presentation gives an overview of all types of BMC concepts and illustrates how the classification tree is organised.

This study intends to develop a framework for classification. A systematic presentation of each concept and their relations is therefore a part of the methodology. Presentations of the results for each concept are organised after the same template. This starts with a short introduction explaining the intention of the concept. The principle is illustrated with graphical presentations with the supplement of a short supporting text. This expresses the relation between information in the BIM and the processes in the rules by use of circles or Venn diagrams. The intention is to express distinguishing characteristics between the concepts. The elements within each concept can be complicated and need separate explanation for nuanced understanding. It will be too extensive to be included in this paper. The ontology part is presented as a short checklist, taxonomy, with characteristics to identify which concept a specific BMC solution can be classified into. The last section for each concept give examples of current use, and proposals for future use. The examples intend to illustrate a way of systematic thinking for how the concepts can be utilised, based on an awareness of the relation between rules and BIM file content. To illustrate the relations between all concepts, these are presented in a separate section including Resource Description Framework (RDF) triples statements, RDF/XML serialisation and an RDF-graph. This approach indicates how the support of ontology and Linked Data contributes to the development of the framework for classifying concepts for BMC.

3. RESULTS

3.1 Concept type 1: Validation checking

The intention with validation checking is to verify that the designed solution in the BIM is within the defined rules in the rules set. Rule sets can be based on multiple sources like codes, standards, contracts, best practice, or by other defined requirements. Clash detection is the most common used example of validation checking, while code checking is an example of a popular type of checking, but with limited implementation.

Principle

The principle of validation checking compares constraints in an information model against pre-defined constraints in rules. A rule set is a collection of rules, normally with a defined theme, such as accessibility of bathrooms. To be in compliance, the constraints in the model must be within the constraints of the rule. Figure 1 presents a visualisation of this concept by comparing two separate elements.

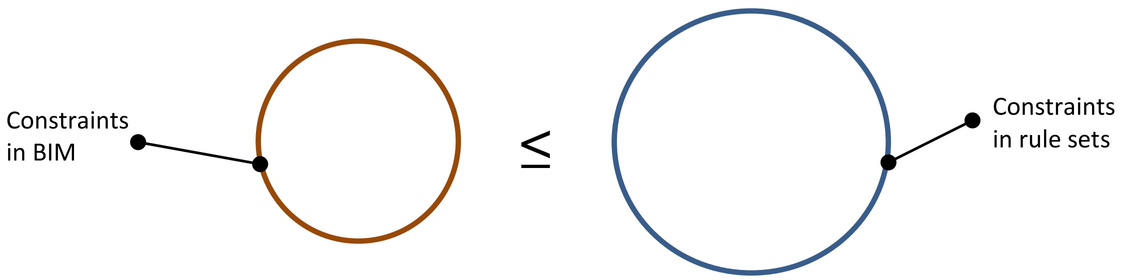


Figure 1: Principle of validation checking.

Figure 2 shows another way to illustrate this principle by the use of Venn diagrams. Situation a) illustrates a case where the constraints in the BIM are within the constraints in the rules. (The circles are placed non-centric to illustrate that it is not about size or location of building parts, but about constraints.) Situation b) illustrates a case where compliance is satisfied for some of the rules in the rule sets, while some rules report non-compliance. There will also be some rules that are not checked, due to lack of information, or because they are not relevant. Reporting must therefore include what is not checked and what is checked to become a trustworthy check for practical impact.

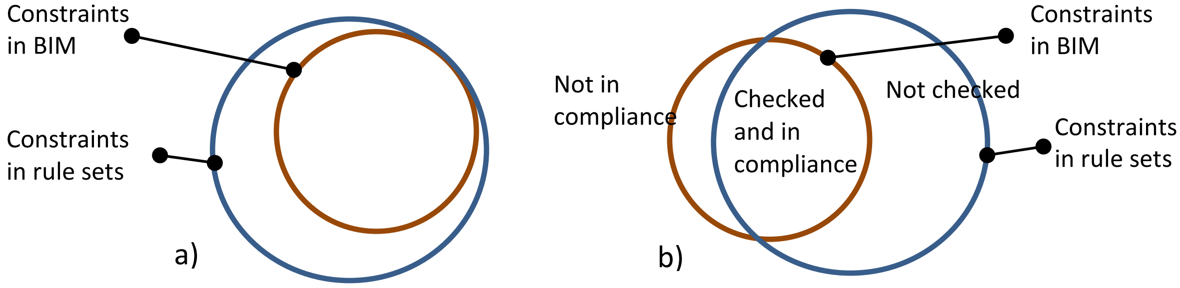


Figure 2: Validation checking illustrated as Venn diagrams.

The purpose with compliance checking is to determine whether the content in the model is in accordance with a code, standard, regulative etc. The logic in compliance checking is based on processing of predefined criteria where the outcome can be: "Pass," "Fail," or "Not checked" (- if the rule is not activated due to missing information). The structure of the validation process is illustrated in Figure 3. The rule set can have constraints which set the limitations of values, or existence / non-existence of an object (e.g. the checking will not valid for a specific type of building, or building with specific solutions like tilted walls, indicating high complexity of the building). Feedback will be given why the checking is not performed.

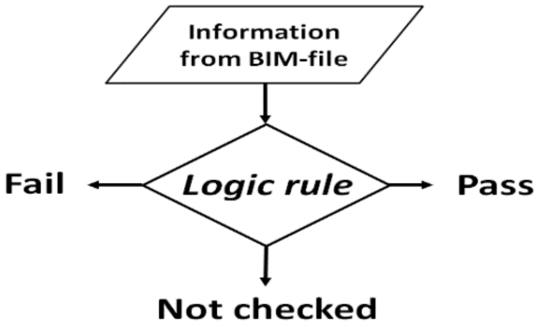


Figure 3: Principle of validation checking

BMC uses information (geometry, text, numbers, and relations) from the BIM-file as input for processing the rules. An example of checking would be: "Check if the door width is equal to or more than 800 mm." If the BIM-file contains information about a "door object" with a property named "door_opening_width" (also used in the rule) with the value "800 mm," then the result is "Pass." If the value is "750 mm", the result is "Fail." If the BIM-file does not contain information about the property "door opening width," or this is specified as "width-of-door," then the outcome is "Not checked." Exact correspondence between content of information in the BIM-file and required information in the rule is essential for trustworthy performance of the checking.

Ontology

Specification of the concept is a classification based on a predefined taxonomy presented in Table 1.

Table 1: Taxonomy for classification of validation checking

Characteristics	Identification
Structure of information:	BIM (a predefined container of information)
Information requirement:	Content of information in BIM in relation to rule
Structure of rule:	Compares defined content against constraints in a rule
Logic in rule:	Information in BIM must be with the constraints in the rule
Outcome:	Pass, Fail, Not checked

Examples for practical use

Validation checking is the most commonly used type of BMC, and a large number of examples can be given. The examples are grouped into geometry and information based checking. The important element is that there is a direct relation between requirements for information in the logic rules for assessing compliance and the information in the BIM file. The specification of computable rules is not included in these examples.

Geometry based checking – Clash detection

Clash detection and checking of component pairs is perhaps the best known concept of checking. When merging models in interdisciplinary collaboration models, this kind of checking is very useful and often included as part of the quality assessment (QA) system. The algorithm (rule) for checking the turning circle of a wheelchair is the same rule that can be used to check minimum / maximum distance from any object to any other object. By enabling parametric selection of objects (in addition to tolerance), it is possible for the designer to check and correct other distances, for example between cabinets for fire extinguishers. The checking is based on topological relationships and Boolean algebra. These rules can also be implemented parametrically, allowing the user to adjust the "rule" by changing the min / max tolerances the components are checked against. (Borrmann, 2008). Because of its geometrical nature, automatic checking can also be easily re-examined by just looking at the 3D model from different angles and sections, and then mark whether this is a failure to be solved or just an over-reporting. The checking is in practice a semi-automatic process with a high degree of transparency in the checking process.

Clash detection has a tendency to report too many "issues". An example of this is when a pipe goes through six different beams, is this one issue or six? Or if a beam goes through six different pipes, is this one issue or six? Normally one would get six reports of errors in both cases, but the answer should depend on rules and the information about the beam or pipe. In an office building, the structural beams may have priority and the expected solution is re-positioning of the pipes. In an oil platform the pipes may have priority and the structural solution must adapt. This example also illustrates the relation between saying what is wrong and what must be done to correct.

Information based checking – Code Compliance checking

The purpose here is to check whether the solutions in the BIM are in accordance with codes, regulations, standards and so on. Automatic management of building permit applications has long been a beacon for model checking. One reason is that approval is a critical point that all facilities have to pass. The first large scale implementation was in Singapore in the CoreNet project for planning approvals.

The rules are often clustered into rule sets for determining the domain to be checked. By combining different rule sets, it is possible to check multiple demands automatically. We do not go into depth on procedures for development of rules. This is a large area with connections to KBE, knowledge based engineering and to AI, artificial intelligence (Hjelseth, 2015). On the other hand, we are now beginning to get standards based on BIM and with Architecture, Engineering and Construction (AEC) industry based approaches in the series of IDM standards.

3.2 Concept type 2: Model content checking

The intention with model content checking is to have an automatic process for checking of the content in the BIM. The intention here is to examine the professional content in a BIM model for a specified use. There is no need for programming of advanced rules, just "filters" for reporting relevant information. This can be further analysed in software as spreadsheets, word processors or databases. This gives this concept great flexibility. IDMs and BIM guidance should then be assisted by content-based checking rule sets, not general specification written as pdf-documents.

This type of model checking is especially relevant at handover of the model, or before processing for calculation and other information intensive activities such a compliance checking. With requirements based on systems like the UK PAS 1192-5 Security, too much information can also be an issue.

Control of content in the BIM is done as an ongoing activity throughout the design process. Automatic content checking has so far been seen as a control activity, and not as a pre-defined check stated in contracts, or in IDMs (specifications according to ISO29481-1 Information Delivery manuals) or in BIM manuals. This implies that requirements in contracts, IDMs and/or BIM manuals should be delivered as digital rules related to content of information. As long as the requirements are delivered for manual interpretation, this remains a time consuming and error prone job. Nevertheless, for each individual projects, this task is still performed manually.

Principle

The principle of model content checking is illustrated in Figure 4. The logic in rule is very simple; the content in BIM is compared with a defined list of relevant information. This checking has two options: identified or not identified. Further action can be to write a report to document compliance. Another action can be to delete specified information, or replace properties with default information.

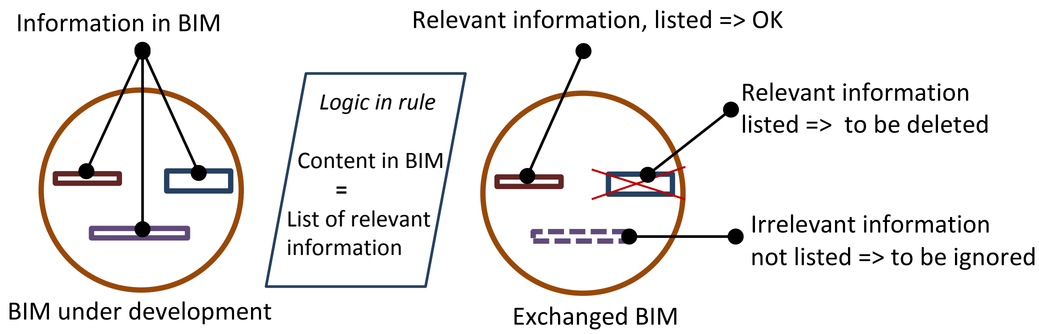


Figure 4: Principle of model content checking

Model comparing is another variant of this principle. The requirement list of content is "replaced" by a new model, and these two models are compared. However, even if the logic in the rules are identical, the reporting of non-compliance will be different. In both variants, the rules and requirements are expressed as relatively simple statements and logic. This is an indication that a solution does not have to be very complicated to be useful for practical tasks, contributing to both time reduction and quality improvement.

Ontology

Specification of the concept is a classification based on a predefined taxonomy presented in Table 2.

Table 2: Taxonomy for classification of model content checking

Characteristics	Identification
Structure of information:	BIM (a predefined container of information)
Information requirement:	Content of information in BIM in relation to list of terms
Structure of rule:	List of predefined terms (properties) compared to properties in BIM objects
Logic in rule:	Identified content in BIM is compared against the list
Outcome:	Identified, Not identified

Examples for practical use

Manual content checking is done as an ongoing activity throughout the design process. What is being checked is normally not formally specified in advance. However, content checking as a systematic and automatic process supporting model quality can be useful in a large number of situations. Paradoxically, the use of content checking can also be used to check whether the model contains too much information as part of the protection of safety, commercial information and/or intellectual property. The examples are therefore grouped into situations with too little information and too much information.

Model completion checking – too little information
This type of checking focuses on identifying compliance between the information in the BIM and a requirement list of specified information. The requirement list with specifications for exchange of information can be based on existing BIM methods such as BIM manuals, BIM guidance, or buildingSMART Processes (bSP). The latter are also called Information Delivery Manuals (IDM) and are based on the ISO 29481-1:2016 standard. Other methods can be Data Drop or Level of Information (LOI) according to BS PAS 1192-2 (under development as ISO/WD 19650 standard). Classification systems can, according to Mêda et al. (2016), be used for specification of relevant information.

This type of content checking can be part of the information exchange procedures to support collaboration during the life cycle of building projects. Hjelseth (2010) has developed a conceptual solution for exchange of relevant information in BIM-objects, defined by the role (task to perform) and phase in life cycle of the project. The importance of maintaining clients' requirements through the life cycle is emphasised by Kiviniemi (2005). The general findings were that clients' requirements were reduced though the design and building process. A design process, and its objects, pass through different stages from proposal to demolishing. The change of status can be checked for keeping track of the process. This will also give improved control of clients' demands and how these are satisfied.

Protection checking – too much information
This type of checking intends to secure that the model does not contain information that we do not want others to have access to. This can be related to safety and security issues, where anything from general information about ventilation or electricals system to specific solutions like the access or security systems are completely removed. It can also be related to commercial information and/or intellectual property that can be useful for internal works, but which is removed before transfer (export) of the model for use by others. The BS PAS 1192-5 is in this respect a very good example of the importance of this approach.

Contributions in architectural competitions can be another situation for the use of this type of checking. The submitted BIM model from the architect is submitted to the BIM-server, where information about "Author", nationality and other information is removed before the jury and others have access to the model. The Norwegian Statsbygg used this solution in the international architectural competition for the new National Arts Museum in Oslo (PNN, 2016).

3.3 Concept type 3: Smart object checking

The intention with smart object checking is to let the object itself observe its environment and automatically adapt to this by embedded pre-defined rules or algorithms. Use of smart objects contributes continually to the update of designs.

Principle

Smart objects are objects which have embedded rules that respond to change in other selected objects. This can be done by embedding rules into the objects. Parametric objects are a sub-type of smart objects, but smart objects can be "smarter" by having more rules, and also respond to non-geometrical properties like specification of material properties. The essence is that the smart object automatically responds to pre-defined changes in the design, like cells with formulas respond to change of input in selected cells in a spreadsheet.

Figure 5 illustrates this principle by an object in a model, where smart object A) automatically responds to change in the design B) and C) according to pre-defined rules (which can be advanced algorithms/calculations).

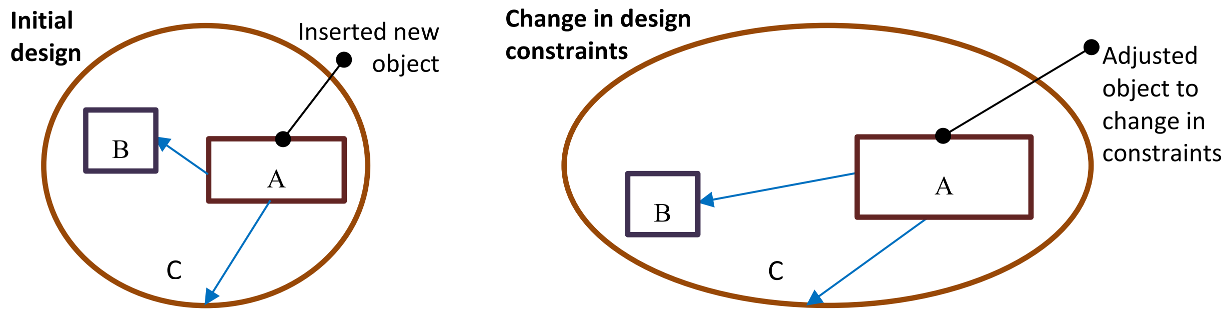


Figure 5: Principles of smart objects and response to update of design.

Ontology

Specification of the concept is a classification based on a predefined taxonomy presented in Table 3.

Table 3: Taxonomy for classification of smart object checking

Characteristics	Identification
Structure of information:	Selected objects in a BIM
Information requirement:	Defined content of information in selected objects
Structure of rule:	Rule is embedded into the (smart) object.
Logic in rule:	Respond on change in defined objects according to a pre-defined rule / algorithm
Outcome:	Object in BIM adapted (geometry, property, position) to the designed solution of the building

Examples for practical use

Examples in practical use in the construction industry are so far limited. Software like Revit have functions to include rules for controlling behaviour of objects by adding formulas to the parameters in the objects. A bachelor theses by Vogt et al. (2016) illustrates the use of smart objects related to scaffolding and safety based rules (regulation). The scaffolding object in Revit had embedded rules which gave warnings when a defined height was exceeded, and added railings to the platform.

Design of window solutions can be another example; where (A) represents the smart object, which is a window. Behaviour / response of (A) is related to (B) and (C), where (B) is a door with window/glass and (C) is type of room and area. Type of room requires a defined area of window to enlighten the room, e.g. 10%. A change in area of the room will trigger adaptation in the smart object (A).

Fire rating can be yet another example, where door and window specifications change dependent on the fire rating of the walls in which they occur, or the spaces they bound. Change of design, such as changed use of buildings/rooms or equipment, which trigger change in hazard class, will then imply that fire rating of the doors becomes updated. This adaptation does not necessarily result in visible geometrical charges, but can be related to properties of the doors or windows.

The adaptations in smart objects can be based on codes or best practice defined rules or algorithms, calculations, heuristics or preferred solutions. Development of smart objects can be part of the company's intellectual properties and quality assurance solution. The final design can be checked by validation checking, which can have more rules embedded into smart objects.

3.4 Concept type 4: Design option checking

The intention with the design option checking concept is to guide the designer to consider a larger range of realistic solutions than is practical without this support. This is particularly relevant in areas where the designer is not an expert or experienced. This type of checking is related to knowledge based engineering (KBE, 2016). This type of solutions is at a very immature level in the AEC industry, and dedicated software solutions are not known.

Principle

The principle of design option checking is based on rules that identify a predefined situation, and based on this make a search for relevant solutions to be considered. This search can be based on a "knowledge database". The database can be an internal database or "archive of design solutions", or it can consist of search rules for relevant solutions. This Support of reference libraries such as International Framework for Dictionaries / buildingSMART Data Dictionary (IFD/bSDD) can, according to Bell et al. (2009), contribute to increased validity by more accurate identification of relevant products and their properties.

Figure 6 illustrates design option checking where the "design system" exchanges constraints about the design solution to an external knowledge database, which processes this information according to pre-defined rules (algorithms) and proposes relevant solutions to be considered. The rules can include that all proposed products must comply with national codes.

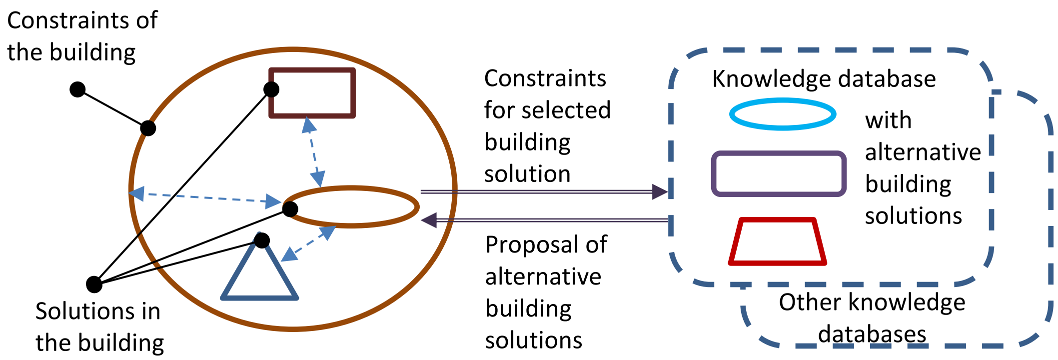


Figure 6: Principle of design option checking

Ontology

Specification of the concept is a classification based on a predefined taxonomy presented in Table 4.

Table 4: Taxonomy for classification of design option checking

Characteristics	Identification
Structure of information:	Selected objects in a BIM in addition to a knowledge database with building solutions (objects)
Information requirement:	Objects in the BIM includes defined characteristic (classifications) for grouping in components (building solutions). Knowledge database includes classifications of building solutions
Structure of rule:	Rule is implemented in external knowledge database(s). Part of knowledge system.
Logic in rule:	Compare criteria in designed BIM in relation to relevant options after search in knowledge database(s)
Outcome:	Proposal for relevant technical solutions

Examples for practical use

This type of model checking is an example of knowledge based and active computer based support of the design process. This enables a positive answer to the question if all other options are checked out. The quality of the question is of course related to how advanced the solutions are. However, even limited support of other options can have significant impact on the designed solution because the feedback is offered as part of the ongoing design process. It is therefore possible to include some of the proposed suggestions.

An elevator can be used as a case. The architect is to design a three or four storey building. The building regulations require elevators in buildings of four storeys or more. The cost/benefit of adding a fourth storey can be established in several ways. One possibility is of course that the architect has very good insight in both regulations and the latest solutions for elevators, or he can include an elevator expert in the design team. A better solution might be to let the software make a recommendation. Another aspect is that this motivates one to go a step further before one turns down a solution as being too expensive, complicated, and not possible here – and so on. Selection of specific products is therefore not the scope of this type of checking, but to be aware of the constraints for different types of solutions. The checking can be embedded in all stages and by all actors in the design process. This concept for model checking can also be regarded as a "learning system" or "experience utilization". This will have some similarities with web-shop services where one receives information about other customers' choices or recommended/related products.

Knowledge-based engineering (KBE) is the application of knowledge-based systems technology to the domain of manufacturing design and production. The design process is inherently a knowledge-intensive activity (KBE, 2016). This type of design process is used in other industries such as aero-, automobile-, oil- and gas industries. Regarding implementation in the construction industry, examples are rare, even though the concept has been known for long time. ITcon had a special issue on architectural informatics in 2006 (ITcon, 2016), but this was perhaps a bit too early. More recently there was a study by Jubierre & Borrmann (2015) about knowledge-based engineering for infrastructure facilities. The increasing maturity and use of BIM is enabling new possibilities, and one can expect an increasing support of KBE systems.

3.5 Ontology – Linked Data by the use of RDF-triples and -graphs

Use of Linked Data is a good way to illustrate the logic relationship between the concepts of BMC. Linked Data can enable machine readability/machine interpretability, which again can enable automatic classification. This type of solution can be further developed into search engines, and will result in in higher precision BMC related searches. Presenting concepts as Linked Data can be used to test the relation within and between different concepts. Another aspect is that this type of graphical presentation also can contribute to an improved overview of the concepts.

Linked Data can also be presented as RDF-graphs. The Resource Description Framework (RDF) is a standard model for data interchange on the Web (RDF, 2014). The RDF extends the linking structure of the Web by using URIs. A Uniform Resource Identifier (URI) is a string of characters used to identify a name or a web resource. URI consists of locators (URL) and names (URN) to name the relationship (predicates) between things, as well as the two ends (subjects and objects) of the link. This is usually referred to as a "triple". Using this simple model allows structured and semi-structured data to be mixed, exposed, and shared across different applications. An example of RDF-triples is presented in Table 5.

Table 5: The four BMC concepts structured as RDF-triples

Relations – as basis for questions about characteristics *Start Node*	*Edge Label*	*End Node*	Relation to types of BMC concepts			
Subject	*Predicate*	*Object*	*1*	*2*	*3*	*4*
Concept_Type	related_to	Content_in_BIM	1			
Content_in_BIM	compared_to	Compliance_Criteria	1	2		
Content_in_BIM	activates	Design_Solution			3	4
Compliance_Criteria	results_in	Compliance_outcome	1			
Compliance_Criteria	identify	Content_outcome		2		
Design_Solution	adapt	Object_adaptation			3	
Design_Solution	match	Solution_outcome				4
Compliance_outcome	is	Pass	1			
Compliance_outcome	is	Fail	1			
Compliance_outcome	is	Not checked	1			
Content_outcome	is	Identified		2		
Content_outcome	is	Not identified		2		
Object_adaptation	activates	Geometry_adaptation			3	
Object_adaptation	activates	Property_adaptation			3	
Object_adaptation	activates	Position_adaptation			3	
Solution_outcome	propose	Relevant_solution_No1				4
Solution_outcome	propose	Relevant_solution_No2				4
Solution_outcome	propose	Relevant_solution_No+				4

World Wide Web Consortium (W3C) offers a free net-based service for RDF/XML validation (RDF-validator, 2006) for validation of RDF triples. This RDF/XML validator accepts an RDF/XML serialization as input. The service also ensures that the document is syntactically valid (can be parsed into triples according the RDF/XML specification) and will subsequently display triples and/or a simple graphical representation of the data. To enable

RDF mapping the "questions" were structured according to Table 5, and validated in the net based by RDF-validator (2006).

The input to the RDF-validator is documented as RDF/XML serialization in Figure 7 below, and the RDF-graph is presented in Figure 8.

RDF/XML serialization as input for the RDF-graphs

```
<rdf:RDF xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
  xmlns:tekrdf="http://www.example.org/">
  <rdf:Description rdf:about="Concept_Type">
      <tekrdf:related_to>
        <rdf:Description rdf:about="Content_in_BIM"/>
      </tekrdf:related_to>
  </rdf:Description>
  <rdf:Description rdf:about="Content_in_BIM">
      <tekrdf:compared_to>
        <rdf:Description rdf:about="Compliance_Criteria"/>
      </tekrdf:compared_to>
      <tekrdf:activates>
        <rdf:Description rdf:about="Design_Solution"/>
      </tekrdf:activates>
  </rdf:Description>
  <rdf:Description rdf:about="Compliance_Criteria">
      <tekrdf:results_in>
        <rdf:Description rdf:about="Compliance_outcome"/>
      </tekrdf:results_in>
      <tekrdf:results_in>
        <rdf:Description rdf:about="Content_outcome"/>
      </tekrdf:results_in>
  </rdf:Description>
 <rdf:Description rdf:about="Design_Solution">
      <tekrdf:identify>
        <rdf:Description rdf:about="Object_adaptation"/>
      </tekrdf:identify>
      <tekrdf:match>
        <rdf:Description rdf:about="Solution_outcome"/>
      </tekrdf:match>
  </rdf:Description>
  <rdf:Description rdf:about="Compliance_outcome">
      <tekrdf:is>
        <rdf:Description rdf:about="Pass"/>
      </tekrdf:is>
      <tekrdf:is>
        <rdf:Description rdf:about="Fail"/>
      </tekrdf:is>
      <tekrdf:is>
        <rdf:Description rdf:about="Not_checked"/>
      </tekrdf:is>
  </rdf:Description>
  <rdf:Description rdf:about="Content_outcome">
      <tekrdf:identify>
        <rdf:Description rdf:about="Identified"/>
      </tekrdf:identify>
      <tekrdf:identify>
        <rdf:Description rdf:about="Not_Identified"/>
      </tekrdf:identify>
  </rdf:Description>
  <rdf:Description rdf:about="Object_adaptation">
      <tekrdf:adapt>
        <rdf:Description rdf:about="Geometry_adaptation"/>
```

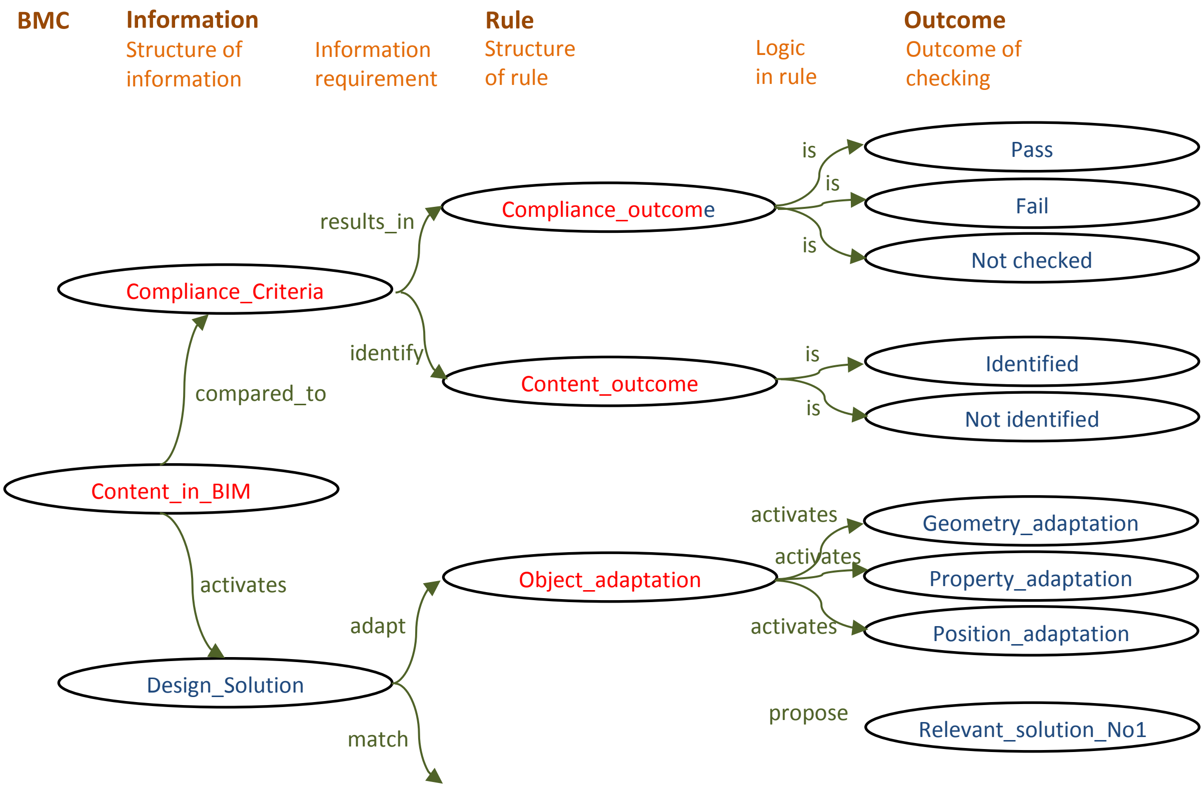
```
        </tekrdf:adapt>
        <tekrdf:adapt>
          <rdf:Description rdf:about="Property_adaptation"/>
        </tekrdf:adapt>
        <tekrdf:adapt>
          <rdf:Description rdf:about="Position_adaptation"/>
        </tekrdf:adapt>
```


Figure 7: The original RDF/XML serialization as input for the RDF-graphs – to be continued


```
    </rdf:Description>
    <rdf:Description rdf:about="Solution_outcome">
        <tekrdf:propose>
          <rdf:Description rdf:about="Relevant_solution_No1"/>
        </tekrdf:propose>
        <tekrdf:propose>
          <rdf:Description rdf:about="Relevant_solution_No2"/>
        </tekrdf:propose>
        <tekrdf:propose>
          <rdf:Description rdf:about="Relevant_solution_No+"/>
        </tekrdf:propose>
    </rdf:Description>
  </rdf:RDF>
```


Figure 7: The original RDF/XML serialization as input for the RDF-graphs

The RDF-graphs of the four concepts of BMC are illustrated in Figure 8. This type of graphs is automatically generated by the RDF-validator (2006). The original graphical presentation from the RDF-validator is hard to read in format of this paper, and is therefore redrawn. A subject linked to a predicate becomes an object. This object can in the next link be used as a subject – and thus enable linking of data. The colour coding in Figure 8 corresponds with Table 5 and Figure 7 in the following way: The objects in blue text in the ellipsis presented without the URL prefix. The original graph from the RDF-validator presents the predicate as red text. To illustrate the predicates more clearly, they are presented as green text at the arrows connecting the objects. A heading with references to the taxonomy in Table 1-4 is included to illustrate the relation to the framework for classification of BMC concepts.



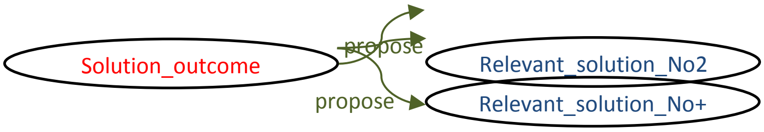


Figure 8: RDF-graphs of the concepts of BMC (modified for presentation purpose)

The graphical presentation in Figure 8 follows the semantic structure (linking) of data and is independent of order in the RDF/XML-structure in figure 7. Use of Linked Data enables dynamic extensions by linking this structure into other structures, and realizing hyperbolic maps. This RDF-graph can, in addition to illustrating the structure of BMC, also represent a way of thinking about BIM as information modelling for the built environment. This way of structuring information into ontologies can enable further integration of information structures. A case study by Beetz et al. (2009) documented that EXPRESS schemas can be transformed into ontologies. This ontology was named IfcOWL. According to Pauwels (2014, 2015) IfcOWL is added into IFC4 addendum 1, and collaboration between W3C and buildingSMART is established for further development. Use of RDF in development of framework for classification can enable further integration with ongoing research activities.

4. DISCUSSION

This paper has described the development of a framework for classifying Building Information Models (BIM) checking concepts. The use of this framework has resulted in four types of BMC: 1) Validation checking, 2) Content checking (which can be grouped into Compliance checking), 3) Smart objects checking, and 4) Design option checking (which can be grouped into Design solution checking). This classification is based on characteristics related to information and rules. One motivation behind the development of this framework was the lack of definitive concepts for BMC in the domain. The intention was therefore to enable the understanding of the concepts and not simply introduce a naming system, which could have been achieved more easily with the use of index lists. Other frameworks for classification can of course be developed by the use of different characteristics. One of the most known systems is the binominal nomenclature for classification where Carolus Linnaeus (1707-1778) devised a system for classifying plants by sexual characteristics (Robin, 1992). Plants can be classified by other characteristics for other purposes, such as to determine which plants are allowed to be cultivated based on chemical ingredients, like hemp for rope or hemp for dope (Owen, 2016). Choice of characteristics is purpose related. Use of characteristics as information and rule can therefore be discussed in relation to the understanding of concepts.

Stringent classification can be challenging to perform in practice. According to Sowa (2006), the challenge is to reduce the "knowledge soup" made of: a) Over-generalizations, b) Incomplete definitions, c) Conflicting defaults, and d) Unanticipated applications. The limited number of types can be discussed, but is to be kept as low as possible to reduce interference between the concepts. Four is the lowest number of unique concepts the chosen characteristics in this study were able to define. Introduction of linked data and use of RDF graphs can in this respect be a test to verify how new characteristics will affect the structure of concepts. The proposed fixed number of four concepts is therefore only a response to the selected characteristics. Different characteristics can of course result in other ways of classifying concepts – and then use Linked Data to verify the logic in relations. This thinking enables both a dynamic way of structuring concepts, and at the same time precisely defined characteristics that can reduce the "knowledge soup" in understanding of BMC.

It is important to be aware that the term used for naming concepts is just a label (Ogden & Richards, 1923). The concepts could be labelled as Type A, B, C or D. It is in general hard to establish a naming convention for wide use. The labelling can be discussed in this respect. This is why an ontological aspect is chosen instead of a linguistic approach, starting with a search for most used terms in BMC related use cases. Looking into marketing from dominating actors such as Solibri, the terms Compliance control, Design review, Analysis and Code checking are used (Solibri, 2016). Navisworks uses terms like Clash detection, Interference checking and Model review (Navisworks, 2016), and Tekla BIMsight uses the term Check for clashes (Tekla BIMsight, 2016). Attempting to obtain a joint understanding by comparing terms like "Design review" from Solibri and "Model review" from Naviswork is not possible. Use of the proposed classification system can enable mapping to specific types, and mapping the types can identify whether Solibri and Navisworks are performing the same type of BMC. This study does not go into a third level, and define e.g. clash detections as a subgroup of validation checking. The classification system is intended to support use of a joint vocabulary and understanding of how different checking solutions can be mapped or classified into defined types of BMC concepts.

The need for an overview of the functionality of rule checking systems can be illustrated by a study from Eastman et al. (2009). This study focuses on the rule checking process and presents four classes of functionality a rule checking system should support: Rule derivation, building model preparation, rule execution, and rule reporting, and their needed internal capabilities.

Different frameworks for classification have different purposes. Solihin and Eastman (2015) have conducted an interesting study where they propose to classify rules for BIM Models according to their computational complexity. The four classes in this framework consist of: Class 1 — Rules that require a single or small number of explicit data, Class 2 — Rules that require simple derived attribute values, Class 3 — Rules that require extended data structure, and Class 4 — Rules that require a "proof of solution". The intention is to classify outline prerequisites for effective rule checking tools and to offer a systematic approach to help progress in research and development. Hjelseth (2015) introduced a methodology to determine which requirements in a regulation that are applicable for implementation into computable rules in BMC. A combination of the solutions presented above can be useful in the development process from interpreting regulations to implementation into BMC software. It is therefore important to be aware that the classification system proposed in this study focuses on classification of concepts for model checking, and by this is not in contradiction to the above frameworks.

An important goal of this study has been to create awareness of the importance of having rules as a separate service independent of software implementation. This concept study does not explore the technological aspects. Further studies following up concepts for BMC should focus on scalable solution for development of rules separated from technology.

5. CONCLUSION

This paper gives an overview of concepts for BIM based model checking concepts summarized in table 6. The classification uses a taxonomy built on Structure of information, Information requirement, Structure of rule, Logic in rule, Outcome to identify group, and type of BMC concept.

Table 6: Overview of concepts of BIM-based model checking

Concept group	Concept type	Purpose of checking	Outcome	Examples
Compliance checking	**Validation checking**	Validation	pass/fail	clash detections code compliance
	Model content checking	Content of information	a filtered list	relevant information for exchange
Design solution checking	**Smart object checking**	Integration (adaptation)	a modified model	size of building parts (objects) related to the building (model)
	Design option checking	Guidance	options and advice	knowledge system for selecting relevant solutions

Compliance checking is performed as a separate process, assessing the design process at predefined or agreed times. The checking is normally done by importing the building model into a specialised software for model checking against a set of rules. This type of checking can be part of the quality assurance system (QA) of the BIM execution plan, or other systems.

Design solution checking will normally be done as a continuous support to the design process. This approach has similarities to knowledge based engineering used in other industries like aero-, automobile-, oil - and gas industries. Rules can be embedded into connected objects or external knowledge databases.

Separating rules from technology has been an important aspect in the classification of types. Specifications of rules can be regarded as a separate deliverable independent of software. Rules are "canned knowledge" or explicit requirements that can be processed by support of BIM based software solutions. Based on this, rules can be developed based on multiple sources such as codes, standards, best practice, and project based requirements.

The potential of BIM based model checking (BMC) has an unrealised potential to change and improve the entire design process in the construction industry by utilising dedicated rules. Awareness of different types of BIM based model checking concepts can contribute to increased understanding and awareness of this potential.

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