# Foundations for BIM-based model checking systems

Transforming regulations into computable rules
in BIM-based model checking systems

*Prinsipper for BIM basert modell sjekking*

*Omforming av bestemmelser i regelverket til digitaliserte regler*
*i BIM-baserte systemer for modellsjekking*

Philosophiae Doctor (PhD) Thesis

Eilif Hjelseth

Department of Mathematical Sciences and Technology
Norwegian University of Life Sciences

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# Preface

This study is about methods for structuring of regulations by reduction of complexity as part of preparation for BIM (building information modelling) based model checking solutions. Use of BIM-based technology for model checking enables a number of opportunities above clash detection of geometry. Checking of compliance with regulations (law, code, guidelines and standards) based on content of information in the BIM file, checked against computable rules interpreted from of text and numbers in regulations will be a range of application of high value for the AEC (architects, engineers and contractors) industry. Due to the high number of regulations is priority given to methods for transforming the applicable part of the regulations into computable rules in an efficient way. Simplicity in methods by manual and semi-automatic procedures for transforming regulations is preferred in relation to interpreting of complex regulations or use of advanced technology for automatic interpretation. This study intent to be a contribution to the first step in the process of increased use of BIM-based model checking. Following steps will be programming into software and implementation into procedures for practical use in the AEC industry.

This PhD study was carried out between 2009 and 2015 at the Department of Mathematical Sciences and Technology (IMT) at The Norwegian University of Life Sciences (UMB), renamed NMBU in 2014. The idea of starting the PhD study came into being in the last period of my fixed-term job as assistant professor at The Norwegian University of Science and Technology (NTNU). Trying to introduce BIM-based education in 2004 was not an easy task. Education at university should be research-based – and with no research – no education, and as a consequence of this – no position after the fixed term. Working with BIM continued with increased effort in my new job as a system engineer in the research department at Selvaag Bluethink, a branch of one of the largest Norwegian private contractors and real estate developers. Being active in the Norwegian Chapter of the International Alliance for Interoperability (IAI), now called BuildingSMART, gave me a great awareness of the need in the market for improved software tools and new processes – but also the problem that the industry had to specify what information they needed for which purpose at which time from which actor in which role. I then got the role as educational coordinator. My work was to bring the interest in BIM and IAI (now re-branded to BuildingSMART) to the students and professors (teachers) in schools. This also included lecturing at a master-classes conference and BIM mentoring for a total of 24 bachelor and master theses at different universities and university colleges. I was offered a 20% research position for one year in the construction and architecture section of IMT – the Dept. of Mathematical Sciences and Technology of IMT. The colleagues and students at IMT created a very inspiring working environment. The best way to continue being part of the BIM team at IMT was to continue as a PhD student. Positive support from Selvag Bluethink, encouraging in relation to my research, enabled me to accomplish the PhD study in combination with my job, or, from my point of view, to be a PhD student and in addition be part of the implementation of BIM in industry.

Selvag Bluethink was reorganised and the first phase of the study was carried out in combination with a part-time job at Standards Norway (2008–2012) and the Norwegian Building Authority (2012–present), except for a period as full-time PhD student from January to August 2012. At Standards Norway I worked as ISO secretary for TC 59 "Buildings and civil engineering works" and SC 13 "Organization of information about construction works" with the development of BIM-related standards. Practical support for professional work in these committees was part of this position. In a working group on the IDM standard, I also met Jeff Wix, who become my mentor and introduced me to international industry and to the CIB W78 and the ECPPM research community.

The PhD study itself has been completed without external funding, but with one big exception, the period from January to August 2012, when I was full-time student funded by Kari – my wife.
The last phase of this PhD study has been done in combination with a part-time job at the Norwegian Building Authority. My job here is related to development of the ByggNett program, digitalisation of regulations and the development of BIM-based model checking systems.

Attending scientific conferences and presenting papers at CIB W078 “IT in construction” (annual conferences) and ECPPM (European Conference of Product and Process Modelling) (bi-annual conferences) has been a good motivation and has provided important guidance in my study. Being a member of the scientific committee in ECPPM in 2012 and 2014, and CIB W78 in 2015, has given me good experience in the peer-assessment system.

Close collaboration with the industry has been an important aspect of this thesis. Part of the work has been implemented in development of regulations and rule-sets. The RASE methodology has been used by BREEAM (2014) in the UK for transforming their requirements into computable rules. The Norwegian Building Authority has started to develop an application based on the RASE methodology.

## Acknowledgements

This thesis, the result of five years of work, would not have been possible without support from a number of people. I would therefore like to express my gratitude to all those who gave me the opportunity to start and complete the PhD study.

First of all I would like to thank my supervisors, Professor Thomas Kringlebotn Thiis and Professor John-Petter Langdalen, for their support and supervision. Their trust in my plans and way of thinking, even in situations where I had trouble explaining my concepts, has been very important. This freedom has been essential for giving me the flexibility to accomplish the PhD study in combination with other commitments.

A special thanks to Jeff Wix, who suddenly passed away on 3rd July 2009, after only one year of collaboration. His positive attitude, including his network of relevant persons, motivated me to join the CIB W78 "IT in construction" and ECPPM (European Conference of Product and Process Modelling) research community. The annual meetings of CIB W78 and bi-annual meetings of ECPPM were very important to benchmark my scientific level and relevance. Feedback from colleagues at these conferences was important guidance in my study.

The collaboration with Nick Nisbet was important for developing the theoretical foundation for the RASE concept. Even though some practical experience indicated that this concept could be useful, the theoretical foundation was missing, but was required for scaling up and enabling trustworthy results.

I am also grateful to Lars Aasness, former colleague at Standards Norway, for his effort to improve my style of English writing in the papers. His positive encouragement to 'Keep calm and carry on' (maybe influenced by his architectural study in the UK) was of great value.

Insightful comments from Professor Bjørn Erik Munkvold at University of Agder (UiA) in the last phase were very useful in finalising this thesis.

However, the most regular contact during the PhD has been with my good friend Professor Tor Guttorm Syvertsen (TorG) at Norwegian University of Science and Technology (NTNU). His almost daily e-mails, critical attitude – sometimes maybe too critical - and his urging to think for myself and make independent assessments have been a motivation for academic studies and further research. Also his critical thinking has been inspiring. When people and organisations claim that: "BIM is the solution!" – his pinpointing remarks to this is always: "What was the question again?…"

To my wife, Kari Lillestrand Hjelseth, my deepest thanks for your patience and understanding of the priorities in my use of time. A special thanks to my three lovely children, Siri (girl, age 9), Simon (boy, age 7) and Susanne (girl, age 5) for tolerating a father sitting (too) much in front of the computer. I hope they will someday believe that I have not spent most of the time playing games. "But you are sitting in front of the computer all the time…" has been an argument I often encountered when I was telling them that they had been sitting too long in front of the computer and must quit. However, this dissertation an indication that I really was not playing on my computer……

Ski, 8th May 2015

Eilif Hjelseth

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# Abstract

Building Information Modelling (BIM)-based model checking is maybe the best way to utilize BIM technology and to contribute to the development of new procedures in the architecture, engineering, and construction (AEC) industry by enabling reuse of knowledge (McHill, 2012). This research seeks to increase the utilisation of BIM-based model checking (BMC) solutions in general, and automated checking of regulations in particular, thereby exploring and suggesting a range of theoretical and practical methods for transforming regulations into applicable digital rules. Regulations include acts and codes with related guidelines and standards.

The target group for use of the developed methods are developers of computable rule specifications – applicable for implementation in applications to be used by the entire construction industry. The specification of the computable rules will then be programmed into software and implemented as new processes for quality assessment of designed solutions or compliance checking.

There has been limited research attention to methods for transforming written building regulations on a large scale into computable rules for BMC that can be specified in an efficient way. This research intends to establish a foundation for the first stage in the development of applicable rules in BMC which can be adapted for use with the major part of the requirements in the regulations which are applicable for digitalisation. Reduction of complexity has been a major guiding star in both the research approach and the development of methods.

The background for this research is deeply rooted in the needs of the AEC industry (architects, engineers, contractors). BMC rules are today mostly focused on clash detection by use of simple geometry-based logic for the conjunction of different parts of building elements like beams and ducts. Free space for a turning circle is another example of a rule based on detection of geometrical conjunction. This type of model-checking replaces visual inspection and the need for information and interpretation is limited.
Support of BMC in knowledge-based domains like compliance checking regulations, or compliance with specifications in contracts, is so far limited but is expected to be the new area in BMC. Today's challenge is therefore to express the regulations in a way that enables valid interpretations of computable rules in BMC.

Compliance checking of regulations is mandatory for all projects. Information in regulations is today mostly expressed in text written for manual interpretation by professionals with long experience in the topic. The regulations have to be interpreted, and this interpretation is influenced by the person, or the role (applicant versus officer for building permission). The use of BIM-based model checkers can be a significant contribution to valid interpretation of regulations. BMC can also contribute to checking of regulations that have not been checked due to a lack of awareness of the regulations, or limitations in time and competency. Increased BMC can therefore have a significant impact on the AEC industry.

The use of regulations as constraints for the knowledge system implies that regulations can be interpreted within a limited domain with a known context (legal aspect), use of BIM and information technology (informatics perspective), and the limited resources for research and development (construction perspective). Interpretation and structuring of text is one of the first steps for enabling automatic processing of regulations. Regulations are domain-specific, and construction is a specific domain with a normative text. This approach enables the use of controlled natural language processing (CNL) as a theoretical foundation. Reduction of complexity is a key element for the development of applicable methods to support further development of allocable

rules in BIM-based model checking software (BMC). The focus on ontology and the use of semantic methods from the domain of informatics in the context of AEC regulations contributes to legal interpretations of regulations and their vocabulary in ways that support valid and reliable specifications. By taking the context awareness as a constraint, it was possible to formulate research questions and to prepare for applicable outcomes.

The primary research question is formulated as follows:

***RQ: How can regulations be converted into computable rules in BIM-based model checking systems?***

This delimitation of the research question specifies a limited domain in which the methodologies and expected outcome can be directly applicable. However, the outcome is expected to be relevant for other regulations beyond the building and construction context.

This primary research question is divided into the following three sub-questions:

*Sub-question 1: How can building regulations be structured to support BMC?*
*Sub-question 2: How can structured regulations be interpreted to support BMC?*
*Sub-question 3: How can BMC be developed, maintained and scaled?*

Real regulations from different national codes have been used throughout in the development and testing for the proposed methods to support the conversion of regulations into computable rules in BIM-based model checking systems.

The applicable aspects are illustrated by the close connections to the following methods that have been developed based on the research

- BMC *) BIM-based Model Checking
- RASE *) Requirement, Applicability, Selection, Exceptions
- Tx3 *) Transcribe, Transform, Transfer
- TIO *) Test Indicator Objectives

Development of these methods is supported by the three sub-questions in the following way:

Sub-question 1, "How can building regulations be structured to support BMC?", focuses on *reduction of complexity* by enabling text to be presented as tables which identify where and when the regulation applies (scope), and what are the requirements (constraints).
This methodology enables both an overview and insight into the regulation, as well as leading to predictable implementation into BMC software. The proposed solution to this question is the semantic-based mark-up methodology named "RASE - Requirement, Applicability, Selection and Exceptions".

Sub-question 2, "How can structured regulations be interpreted to support BMC?", focuses on context-related interpretations. The use of domain-controlled natural language processing (CNL) instead of natural language processing (NLP) has been an approach to narrow the scope for enabling applicable solutions. Interpretation of regulations is an especial challenge with performance-based regulations. Not all regulations are capable of being digitalised and some have to be rewritten to enable implementation in BMC. Interpretation and rewriting both focus on understanding terms from both the legal and construction perspectives. The proposed solutions to this question are the "Tx3 - Transcribe, Transform, Transfer" and the "TIO - Test Indicator Objectives" methods.

Sub-question 3, “How can BMC be developed, maintained and scaled?”, focuses on the time, cost and competence or methodology for development of scalable solutions. Answering this sub-question is based on process and combinations of methods related to the complexity of the regulations and the impact of digitalisation on the rules. By introducing a step-wise and iterative process, we look for what is applicable, rather than trying to solve the most challenging regulations. The applicability aspect has been ensured by giving priority to simplicity in the methodology, and including constraints on input to ensure validity. Input in the rule is the type of source text to be converted into computable rules. The complexity of the models of buildings to be checked can also be used to set constraints to increase the validity and reliability of the results of BMC. The connection to BIM and the use of IFC (Industry Foundation Classes, based on ISO 16739:2013) contribute to an open environment for computer systems, both for development and for input into BMC software (applications).

The outcome of this PhD research presents the scientific foundation for methods for transforming regulations into computable rules in BIM-based model checking software. Based on the need in the AEC industry, the developed methods can be utilized as the foundation for digitalisation of regulations into BMC. The transparency of the use of the methods should indicate that the methods can be used by professionals from the AEC industry itself, and not be confined to external consultants only.

The use of the presented methods is included as part of the ByggNett development (Refvik, 2013). ByggNett is an ongoing Norwegian development program managed by the Norwegian Building Authority to initiate digital collaboration between public authorities and commercial / private actors through the entire life-cycle of the building and civil project. The development of self-service digital solutions –initiated both from public authorities and from industry - is generally an approach that has a high priority. The development of solutions for BIM-based model checking is included as a significant contribution in the ByggNett program. The UK’s BREEAM has used the RASE methodology to convert their assessment criteria into a computable form to enable BMC (Sutton, 2014).

The use of BIM-based model checking can influence the design quality and interdisciplinary collaboration in the AEC industry. Contributions from the research can support the development of low-cost solutions for the development of computable rules through the support of the presented methods.

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## *List of abbreviations*

| | |
|---|---|
| AEC industry | Architecture-Engineering-Construction industry. This term is used in an inclusive way and includes Facility Management, Operator and Owner, in addition to related public government. |
| BIM #) | Integrated interpretation based on combinations of: Building Information Model/ - Modelling/ - Management |
| BMC *) | BIM-based Model Checking |
| CNL | Controlled Natural Language processing |
| IDM | Information Delivery Manual |
| IFC | Industry Foundation Classes |
| IFD | International Framework for Dictionaries |
| L+I+C *) | Legal + Informatics + Construction |
| LIM *) | Life-cycle Information Model |
| NLP | Natural Language Processing |
| OWL | Ontology Web Language |
| RASE *) | Requirement, Applicability, Selection and Exceptions |
| RDF | Resource Description Framework |
| TIO | *) Test Indicator Objectives |
| Tx3 | *) Transcribe, Transform, Transfer |
| XML | eXtendable Markup Language |

#) Integrated interpretation of BIM is used in this thesis.

*) New definitions developed as part of the PhD study. These definitions are described as part of the methods developed in this thesis.

## *Glossary of relevant terms*

The intention of this glossary of terms is to introduce the reader to the perspectives used for delimiting the title, or scope, of the case study. The subtitle, "Transforming regulations into computable rules in BIM-based model checking systems", is given to specify the constraints of the approach. A joint understanding will be very helpful to align the formation of expectations between author and reader. The three most relevant terms (in alphabetical order) to be aware of are:

- BIM
- BMC – BIM-based model checking
- regulations
- transforming / converting

These terms have in general a wide interpretation in the industry and no single joint understanding is established. On the other hand, these terms are commonly in use and understanding / misunderstanding is based on context.

***- BIM***

BIM is a much used abbreviation, but without a clear definition. This thesis uses the term in an inclusive way, which includes BIM as building information model/ modelling / management. The relation between these three perspectives is illustrated in Figure 1.

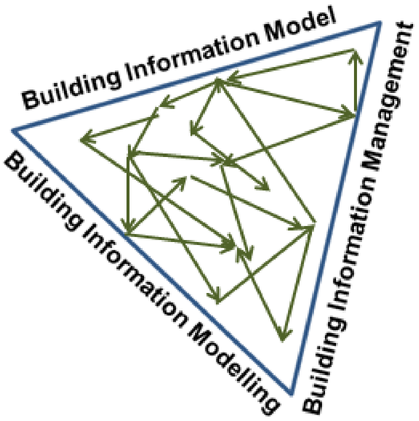


**Figure 1. The trinity of BIM as Building Information – Model – Modelling – Management**

The trinity approach to BIM, Model – Modelling – Management, can be explained briefly as the integration of:

– Model – with a focus on the product.

In this thesis is the term *BIM file* used to express this perspective of BIM. The BIM file is the exchanged unit of stored information transferred between software. This will normally be represented by a file from BIM-based software. If this is exported/imported as an IFC file (based on ISO16739:2013 standard), this is also called OpenBIM. Exchange of information can also be based on web services.

– Modelling – with a focus on process.

In this thesis will BIM be us as abbreviation for *building information modelling*. This use of BIM focus on the process of specifying relevant information required for the processing of rules in BMC. Use of IDM – Information Delivery Manual / bSP buildingSMART Process (based on ISO 29481-1:2010, 2015 standard) or BIM guidance (based on ISO12911:2012 standard or national-, industry-, branch- or company-based specifications) can be references for systematic development of comprehensive solutions.

The information is in general transported (transferred) with the use of the BIM file, but this can also be done as web services (WS). This BIM file can in most cases be regarded as an IFC file, but also as other formats like Construction Operation of Buildings information exchange –known as COBie (East, 2013). This can be exchanged by proprietary formats like the XLS-based Excel format

– Management – with a focus on people.

This use of BIM is related to implementation of BMC and will include procedures of tasks related to roles and responsibilities. This perspective of BIM relates to ISO 9000 - Quality management systems series of standards (ISO 9000, 2014).

***- BMC – BIM-based model checking – public and commercial***

There are some key differences between public and commercial model-checking systems.

Commercial BMC solutions normally start with the BIM technology and focus on what can be practically implemented. If the implemented rules contribute to some improvements during the design process, this is often regarded as good enough for practical use. The rules are (so far) mostly based on covering generic logical rules like clash detection of geometrical objects.

Public solutions normally start with a focus on how the regulations can be converted into computable rules. Transforming performance regulations into computable rules is of high priority. Validity and reliability in interpreting text in regulations is critical. According to Schartum (2012), a public solution requires a very transparent specification of computable rules. They are therefore very suitable as a use case for developing ways of transforming requirements into computable rules in BIM-based model checking systems.

Systems are used as an inclusive term and can be both manual procedures and automatic processing in software. For practical use can combinations be possible, where professional decision support assessment and preparation of facts for decision is provided by BIM-based software.

***- Regulations***

Regulations are used in an inclusive way and cover all normative text, such as acts, laws, codes, directives, standards, etc. Regulations can be defined as normative text, which gives constraints for technical solutions or activities that take place under defined conditions. Another characteristic feature of regulations is that they have a limited vocabulary. This enables dedicated solutions within the domain of AEC industry-related regulations.

***- Transforming / converting***

The terms “transforming” and “converting” can be used as synonyms in literature about the processes of making requirements applicable for digital model checking. In this thesis is the term transforming chosen to be used for this process. The reason for this is that this thesis use standards and public regulations as case – and by this has interpretations that are close to informatics of law (Schartum, 2015). Paper 5 has used the term converting in the title, but could be replaced by transforming. The Tx3 methodology use “Transform” as one of three, and requirements with this classification has to be “re-written” to be applicable for BMC

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# 1 Introduction

## 1.1 The aim of this research

The primary aim of this research is to contribute to improved utilisation of knowledge by increased use of BIM-based model checking (BMC) to enable better buildings and/or a better built environment. One unit of measurement of designed quality is compliance with regulations. Regulations include acts, laws, codes, directives and standards. Regulations can be regarded as knowledge systems – embedded knowledge about how to design, build and maintain to obtain an acceptable level of quality. However, implementation of regulations has so far been limited in BMC systems, both by the authorities and by commercial developers. There are well-developed methods for extracting information from BIM (or the BIM file in e.g. IFC format) and processing this with logical statements in software. There is therefore a paradox that we do not have the same efficiency in interpreting regulations in the systematisation phase as we have in programming and implementation. The presentation of BMC often includes advanced features for processing of rules and presentations of outcomes. The use of rules based on regulations is limited, and when these are included, only single and simple parts of the regulations are implemented.

The applicable aim of this research is to contribute methods for interpreting regulations in a way that is valid, reliable, time- and cost-effective. Interpreting regulations is in general regarded as complicated – and reduction of complexity is used as a guiding star for this work. A multi-disciplinary approach based on simple methods and stepwise processes is given priority instead of optimisation by the use of advanced methods based on technology or methods within one discipline. The three primary roles are legal, informatics perspective and construction, whit focus on integration.

## 1.2 Research position – industry approach

The research is grounded in the AEC industry; the problem involves the utilisation of knowledge to enable better designed buildings (constructions) and the opportunities with BIM-based technology. McGraw-Hill (2012) sees BIM-based model checking (BMC) as one of the emerging solutions for increased use of BIM. The outcome of BIM-based model checking may be the best way to utilise BIM technology, and to contribute to the development of new procedures in the AEC industry by enabling reuse of knowledge.

Quality, performance, cost and income are all influenced by valid interpretations of regulations. These interpretations are today done as manual processes in the AEC industry. The use of automatic processing or decision support is so far limited. Processing of building permit applications is a use-case where automatic processing is expected to have a significant impact. This will allow a significant reduction of processing time, but maybe more importantly, a reduction of uncertainty in interpretation of the regulations, as well as more predictable outcomes of building permit applications.

The AEC industry in Norway, as in most countries, is a highly regulated industry. The regulations consist of legislation (laws/acts, codes and guidance), in addition to standards, both national and international. Designed solutions must be in compliance with the minimum requirements in the regulations. Interpreting regulations related to a current project can sometimes be a challenge, both in verifying that the designed solutions comply with the regulations – and in developing and combining new and innovative systems. According to Standards Norway (2014), there are a total of approximately 4500 standards related to the Norwegian AEC industry. A search performed on 20th December 2013 in the product database of the Norwegian Building authority identified 416 standards related to documentation of products, and identified 50 covering modules of certification (DIBK-Byggevareinfo, 2014).

The development of better solutions for BIM-based model checking is therefore a natural domain of the problem. In simple terms, this extensive domain can be explored in two ways; with a focus on technology and software – a “hard approach”, or with a focus on processing of knowledge – a “soft approach”, and by combinations and variants thereof. Technology, both new solutions and implementations, is developing rapidly. Yesterday’s limitations are decreasing (following Moore’s law?), and have passed a level where the technology itself is not the problem or “show stopper” for practical use. This research has no direct focus on technology, but has this development in mind when focusing on knowledge-based problems. Even if BIM-based model checking is emerging, the development of computable rules is relatively limited. This is resulting in both limited utilisation of technology – and also a lack of putting knowledge into systems that can enable better utilisation and re-use. The “I” in the “BIM” is about information and can be explored with a knowledge-based approach – and related (appurtenant) methods. The constraints in the AEC industry require methods that are as simple as possible, and this excludes research based on optimisation of one single existing method. It is the simplicity and combinations of principles from knowledge management and ontology engineering which is given priority in development of methods for practical use.

## 1.3 Status and development in the industry

*The general digitalisation of society*

The development of the “information society” enables new possibilities. The Norwegian government has stated in its White Paper (Stortingsmelding, 2012) that: *“digital services should be the default in communication with the public sector”*. Increased use of BIM-based software in the design process enables object-based systems containing both information and geometrical representations of designed systems. Developing systems within BIM-based model checking is thereby supported by the general digitalisation of society – ‘the information society’ – and enables new possibilities. This aspect has two impacts:

- expectation of digital services and
- emergence of the use of digital technology.

The first aspect is supported in general by transforming manual services into digital services. Self-service solutions with 24/7 access are preferred by the AEC industry and private applicants. BIM files can in principle contain most of the relevant information regarding the building, with information about the site – automatic processing of compliance in regulations – and with the building permit as the outcome. The practical situation in the AEC industry is not yet at this level. Banking today offers net-based processing of minor loans applications. Society therefore has a similar expectation of the AEC industry. McGraw Hill (2012) has stated that model checking is one of the major impacts of the use of BIM.

The second aspect has several layers, from the general emergence of the use of digital technology in society in general, to dedicated initiatives in the AEC industry. The survey status reports from the ByggNett program (Refvik, 2014) confirm that the governments of Singapore, South Korea and the UK are planning, or have partly implemented, similar developments to the Norwegian ByggNett program.

The combinations of the above are stated by many as one of the most significant impacts of the digitalisation of the AEC industry. There has been development during the five years of this study, but no one has come up with a “final solution”. The research questions are therefore still relevant to be solved. The development of a public rule-set for digital processing of regulations has still not been realised. This academic PhD study does not bring any new software or simple solution to the market. However, it lays the foundations for further development of practical solutions for the AEC industry. The value chain can be illustrated as: *Systematisation* -> *Programming* -> *Implementation*. This thesis focuses on systematisation. Programming is not directly covered, but systematisation emphasises solutions that build on repeating functions and structure. I also make use of existing data schema like IFC (ISO 16739:2013). The combination of the legal, informatics and construction domains enables increased use of digital services for processing of compliance. Model checking (McGraw Hill, 2012) is therefore regarded as one of the major impacts of the use of BIM.

*Commercial systems*
Software systems for model checking are under development. Commercial systems like Solibri Model checker (Solibri, 2014) are mainly based on IFC import. This software has embedded a number of rule-sets for checking for different types of clash detection. Software like NavisWorks (2014) from Autodesk has a main focus on clash detection and coordination of models from different disciplines.

*Public systems*
There is increasing interest from public authorities in developing systems for digital processing of building permit applications. The systems from Singapore are well known. The Norwegian Building Authority had already in 2003 developed a net-based system for submission of building applications. They are now continuing this with a comprehensive program called ByggNett, which includes digitalisation of the entire AEC industry and public sector for processing of building-related information and regulations. The UK initiative for increased utilisation of BIM as the default system for the entire AEC industry by 2017 (Planning Portal, 2014) can be regarded a powerful contribution in this respect. Refvik (2013) found the CORENET from Singapore and the Planning Portal from UK to be the most significant public projects. In addition, he identified projects in the pipeline with similarities to the ByggNett concept in Denmark, Japan and Korea. The EU has recently initiated and funded a similar project in Iceland. An example of an industry-based initiative is the USA-based AutoCode project (2013).

## 1.4 Problem statement

*Unrealised potential – need in the AEC industry*
BIM-based model checking (BMC) is maybe the best way to utilise BIM technology, and to contribute to the development of new procedures in the AEC industry by enabling reuse of knowledge (McGraw Hill, 2012). The AEC industry is highly regulated whit a large number of acts, codes, guidelines and standards to comply with. Use of BIM for compliance checking will therefore be a useful support.

*First mover – systematic approach*
Based on the current situation in the development of BIM-based model checking systems in general and public systems in particular, the problem statement should be obvious: “Start developing model-checking systems – we can no longer check everything manually”. In solving the research problems, I have tried to take the status in the industry into account and to focus on applicable – and scalable – systems. A well-established theoretical basis is the foundation for sustainable systems, where the time required for development, maintenance, further development, and scalability of system is very important for practical use. (Schartum, 2012). The is in general much focus on technology in development of BIM-based model checking solution, but relatively limited focus on systematic approach for specification of rules. This problem looks to have been solved ad-hoc as a disturbing part in programming rule and IFC import. This approach is well suited for development of limited demo applications, but does not scale up when increasing number of rules, or with updating of implemented rules (Dimyadi and Amor, 2013).

*Reduction of complexity*
Reduction of complexity is a key approach for solving the research problems – and for enabling applicable systems. Reducing complexity in the first step of interpreting regulations by creating a controlled environment for structuring regulations into applicable rules is essential for further development. The experience of the Norwegian Tax Administration (Os, 2014) was that the complexity of an IT project increases by a factor of 10 for each step in the development process.

*Real regulations as cases*
Real regulations are used throughout as cases in the research and testing of methods. Regulations include acts and codes with guidelines, in addition to standards. Regulations can be regarded as "best practice" or at least minimum requirements for acceptable systems by society or industry. In this respect, they can be regarded as representing a knowledge system for the design, construction/building/erection, maintenance and use of buildings.

Because all buildings/constructions have to comply with the regulations, they are relevant candidates for the development of automatic processing of building permit applications. However, these problem statements are far too broad for scientific research, and have to be restricted to applicable research questions. The research problems are based on the following delimitations:

*Characteristics of regulations*
- Structured text
- Limited domain of knowledge
- Specified and limited vocabulary – properties in BIM
- Text in real use – high focus on interpretation

*BIM-based delivery of information*
- Use of BIM files (in practice IFC files) as input or information

*Focus on systematisation*
- Reducing complexity
- Methods can be manually applied
- No programming and implementation included

***Research question***
The research question can be formulated as:

*How can regulations be converted into computable rules in BIM-based model checking systems?*

This research question indicates a focus on applicable methods for a well-defined task as regulations, or more building regulations model checking software with input from a BIM file. Use of real regulations for exploring and testing of proposed methods support this applied approach. However, the developed methods is related processing of information and can be knowledge system. The source for transforming text into rule can in principle be any normative test expressing actions or requirements. Examples of this are client requirements or quality assessment requirements of architects, engineers, contractors and operators.

This research question is divided into the following three sub-questions:

***Sub-question 1***

*How can building regulations be structured to support BMC?*

Answering this question can in principle enable the automatic transformation of a regulation statement into an applicable rule and further into executable program code in model checking software. This transformation is based on re-structuring the regulations using a standardised methodology.

The proposed solutions to this question are presented in chapter 5.2 on “Requirement, Applicability, Selection and Exceptions – RASE”.

***Sub-question 2***

*How can structured regulations be interpreted to support BMC?*

Regulations are written to be interpreted by skilled professionals who know the context for their practical use. This is not the situation in BMC systems, where all the information has to be explicitly expressed. The sub-question focuses on theories and methods for interpreting text. The use of controlled natural language processing (CNL) instead of natural language processing (NLP) has been one approach to narrow the scope for enabling applicable systems for interpretation of regulations within the AEC domain (example refs?). Interpretation of regulations is especially challenging within performance-based regulations. Not all regulations are capable of digitalisation and some have to be rewritten to enable implementation in BIM-based model checking systems. Interpretation focuses on understanding terms from both the legal and construction perspectives in a way that enables digital processing (informatics perspective).

The proposed systems to this question are presented in chapter 5.3 on “Tx3 - Transcribe, Transform, Transfer” and chapter 5.4 on “TIO - Test Indicator Objectives”.

***Sub-question 3***

*How can BMC be developed, maintained and scaled?*

This question focuses on time, cost and the required competence for the development of scalable systems. The focus is on the process and combinations of methods related to the complexity of the regulations and the impact of digitalisation on the rules. This is done by introducing a step-wise and iterative process for what is applicable, rather than solving the most challenging regulations. The applicable aspect has been ensured by giving priority to simplicity in the methodology, and instead including constraints on the input to ensure validity. Input in the rule is the type of source text to be converted into computable rules. The complexity of the models of buildings to be checked can also be used to set constraints to increase the validity and reliability of the results of BMC. The connection to BIM and the use of IFC (Industry Foundation Classes, based on ISO 16739:2013) contribute to an open environment for computer systems, both for development and for input to the BMC of software (applications).

The proposed solutions to this question are presented in chapter 5.1 on “BMC - BIM-based model checking”.

## 1.5 Overview of theoretical perspectives

This research takes a multi-disciplinary approach where the aim is to contribute to solve practical problems in the AEC industry. The multi-disciplinary approach includes combining disciplines from the legal, informatics and construction domains.

The development of methods for automatic model checking systems is related to the development of expert systems, but instead of going into depth in artificial intelligence and logic theories from informatics, search contribution from ontology. This theoretical perspective focuses on understanding of “what things are” and not what it is called (Gruber, 1993). This joint understanding is essential to enable semantic interoperability within and between regulations. Regulations can be interpreted in a uniform way which enables formulation of rules that can be generic used on various BIM files of building projects. Importance of the “bridging” legal and construction is by Schartum (2012) as a significant factor for development of systems for digital processing of regulations. Deliberate use of ontology contributes with theories, principles, methods and tools for interpreting legal understanding of regulations into computable rules applicable in construction projects.

Automatic, or semi-automatic, processing of regulations includes interpretation and structuring of the text in the regulations. Regulations are rather domain-specific, and construction is also a specific domain. The interpretation is done from the domain-specific perspective. This contributes to reduction of complexity (Tarski, 1935). This approach enables the use of domain Controlled Natural Language processing (CNL), which is more applicable than a general natural language processing (NLP) approach (Russel and Norvig, 2010; Sowa, 2000). The methods can in principle be used without investment in software. The use of software will of course contribute to faster production and make it easier to maintain control over the large amount of information.

In the perspective of model checking as knowledge system is use or professional input from legal and construction experts an included part. It accepts that not all regulations can be implemented as computable rules, but can be checked by experts from legal and construction domain (semi-automatic systems for model checking).

## 1.6 Results

***Published papers***

The results have been presented in 7 papers published in international journals and international conference proceedings with peer review. All papers contribute empirical or theoretical insights into the main research question of this thesis. The papers and their relation to the research sub-questions are listed in Table 1 to illustrate how each of the papers contributes to different aspects of the phenomenon under study. The grey-scale indicates the degree to which each paper addresses a particular research question. SQ is an abbreviation for research sub-question.

**Table 1. Relationship between focus in papers and the research sub-questions**

| Presented in paper # | Title of paper | SQ1 | SQ2 | SQ3 |
|---|---|---|---|---|
| **Paper 1** | **Overview of concepts for model checking** | | | |
| **Paper 2** | **Exploring semantic-based model checking** | | | |
| **Paper 3** | **Exchange of relevant information in BIM objects defined by the role- and life-cycle information model** | | | |
| **Paper 4** | **Capturing normative constraints by use of the semantic mark-up RASE methodology** | | | |
| **Paper 5** | **Experiences on converting interpretative regulations into computable rules** | | | |
| **Paper 6** | **BIM-based model checking (BMC)** | | | |
| **Paper 7** | **Trustworthy interpretation of normative text by use of ontology** | | | |

Legend:

| | |
|---|---|
| Black indicates high relevance | |
| Grey indicates partial relevance | |
| White indicates limited relevance | |

with the following research sub-questions:

SQ1: How can building regulations be structured to support BMC?

SQ2: How can structured regulations be interpreted to support BMC?

SQ3: How can BMC be developed, maintained and scaled?

which intend to support:

RQ: How can regulations be converted into computable rules in BIM-based model checking systems?

***Developed methods***

The main results of the thesis comprise the development of the following methods:

- BMC BIM-based Model Checking
- RASE Requirement, Applicability, Selection and Exceptions
- TIO Test Indicator Objectives
- Tx3 Transcribe, Transform, Transfer

Each of these methods is explicitly presented in chapter 5 “Contributions”. These methods support the programming and implementation of software systems for BIM-based model checking. The development of software applications has not been part of this study, but the contributions can be regarded as arguments for the development of software applications.

Figure 2 illustrate the conceptual relationship between developed methods.

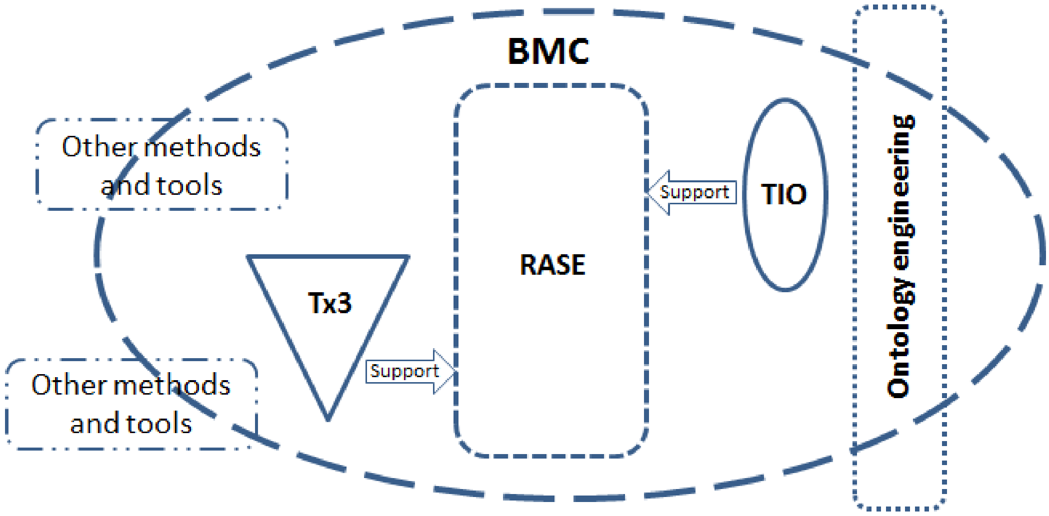


**Figure 2. Conceptual relationship between developed methods**

BMC can be regarded as concept that explains the relation between the other methods. As Figure 2 illustrates can developed methods; RASE, Tx3 and TIO, be supported by other methods – especially ontology engineering related methods – to create a complete development environment for digitalisation of regulations into computable rules. BMC as a method state that development of computable rules can be created as a deliberated production process, and not by various ad-hoc solutions discovered during the development process. Ontology engineering is illustrated as an element through the BMC concept. For practical used does will it be useful to include other methods and tools. Use of dictionary for relevant term is one example for useful support in the work of transforming regulations into rules. Use of software tools for modelling of information flow; as UML class diagram (UML, 2014) or BPMN, Business Process Model and Notation diagrams (BPMN, 2014) for overview of involved roles and process, will increase efficiency in specification and documentation of rules

The RASE methodology has a significant role in structuring regulations into computable rules. RASE identify the scope and requirement of every rule. This can be used as "requirement database" in itself or as specification for programming of digital rules. The Tx3 method for can be used to determine the degree of digitalization in advance of the development process. This will normally be done in the beginning of the development process to set level of expectations. The TIO method can be used to support interpreting of regulations and by this increase implemented units of the regulation. TIO will normally be used in the middle and last period of the project to solve interpretation of function based regulations.

## 1.7 Impact of this research

The outcome of this research can serve as a "first mover" in developing the process of transforming text in regulations into computable rules in BMC. The developed methods have a simplicity that contributes to starting the development processes without investment in software.  This approach enables professionals with a background in the construction and legal domains to be at the head of the development process. The use of external consultants in system development to manage the process can be reduced. Interpretations of regulations are often a challenge, and the increased involvement of construction and legal specialists can create applicable interpretations and reduce the cost of hiring external consultants. The use of the Tx3 methodology can contribute to identifying which regulations or parts of regulations can be expressed as computable rules - related to whichever advanced method has to be used. This ranges from simple transcription (e.g. the opening width of a door must be 900 mm or more is expressed as: door opening >= 900 mm) to support from expert systems. Identification of the degree of digitalization in advance of starting a development project contributes to reducing the uncertainty in the project and to giving realistic expectations.

High validity (trustworthiness) can be achieved by including constraints in the situation where the computable rule can be applied. The use of the TIO methodology contributes with a practical approach to interpreting the qualitative statements that are often used in performance-based regulations. This can be related to certain types of buildings, or the complexity of a building. Increased overview and insight in the regulations is one of the spin-offs from this process, in addition to more realistic expectations of what it is possible to achieve. The increased insight and overview is very important due to the high number of regulations in the AEC industry. The RASE methodology contributes with a way to structure text in regulations into tables, or databases, which identify which regulation contributes with which rules that apply in which situation with which requirements. The overview can be presented in various ways. This can be with tables structured in different colours, for single regulations in small-scale projects, or for a larger-scale project it can be expressed as databases, combining rules from multiple sources. This enables an overview of regulations – and can thus contribute to a reduction of requirements which are coved by other regulations.

This PhD is article-based and some publications have received interest in practical implementation. Sutton (2014) from BREEAM in the UK reported in a presentation on 25 March 2014 at the Norwegian Building Authority (DIBK) about RegBIM (2014) that the RASE methodology was used in the development of applicable rules for BREEAM (2014) assessment. The ByggNett (DIBK-KVU, 2014) has also expressed interest in the RASE methodology as a method for digitalisation of regulations. The Tx3 methodology can been used to specify the degree of digitalisation that is relevant by giving realistic expectations of which regulations can be implemented into BMC. The TIO methodology contributes with constraints for interpretation of performance-based regulations. DIBK has started a project to develop an application (DIBK-RASE, 2014).

Schartum (2013) stresses that the development of future regulations should be adapted to computer-based solutions. In this respect, the RASE and Tx3 methodology can contribute to the development of "computer-friendly" regulations by testing whether proposed regulations can be converted by a simple transcription process, or need to be transformed using more advanced processes to enable implementations into BMC. The outcome of this PhD study can also contribute to a new way of developing regulations and processes where one starts by structuring and then implementing the regulation into the RASE structure. If the regulation can be easily specified with RASE, it can be regarded as computer-friendly, and it is possible to assess whether it covers its intended scope in an applicable way. The regulation can in the next step be formulated as complete sentences.

The economic impact, according to Hauch (2012), can be split into four parts: The first part is the direct effect - by learning and interpreting the regulations. The second part is the indirect effect – by reducing insecure elements in the processing of applications. The outcome of a building permit application can be predicted in advance. Having this as an automatic computer-based process, the results can be processed immediately. On the other hand, doing this manually (due to a lack of digital access to all relevant information) but following the digital process can also be an applicable solution. The third part is the derivative effect – the process of designing can develop more alternatives – and assessment of compliance with regulations. More alternatives can contribute to better selection of design. The fourth part is the potential cost – BIM-based model checking can be used to assess the consequences of future regulations by testing the proposed regulations on large numbers of building projects – represented as BIM-files – and identifying where and how the consequences appear.

An increased focus on BIM-based model checking can have a strong impact on the content and quality of the information in the BIM files. Compliance between the required information for processing the rule and the content of information in the BIM file is a premise for trustworthy checking. This aspect is dual since increased use of BIM-based systems will also be an enabler for utilisation of BIM-based model checking systems. The contributions from this single PhD study are limited and do, of course, not give all the methods for a complete system for the development of computable rules. The development of a software system based on the principles set out in this study is expected to create increased interest in the practical implementation of computable rules. This PhD can motivate the development of other methods to support an efficient development process of computable rules.

## 1.8 Structure of the thesis

This introductory chapter has presented the motivation for this work, placed it in its context, presented the problem, and justified the research questions in focus. Chapter 2 provides background information with an overview of related research and the situation in the AEC industry, including public sector reading use of BIM and BMC. Chapter 3 focuses on the research approach and methodology. Chapter 4 presents an overview of the results, with a brief summary of each of the seven papers. Chapter 5 presents the contributions and key implications of the developed methods. Chapter 6 includes a short discussion about how the research has been done. Chapter 7 concludes the thesis by presenting the answers to the research questions, the limitations of the work, and the implications for further research. Complete versions of the seven publications forming the basis of the thesis are presented in annex A.

# 2 Related research and industry status

## 2.1 Status of research in this field

Model checking in the AEC industry is gaining increased interest due to the use of BIM-based design software (Mc Graw Hill, 2012). The research domain is not clearly defined and ranges from technical issues and capacities in data schemas (IFC/bSDM) to the semantic (IFD/bSDD) and logical challenges of the understanding of language and presentation of rules. Other approaches within the digitalisation of requirements of regulation focus on the legal issues regarding performance-based versus prescriptive regulations, in addition to the challenge of interpreting regulations.
BIM based model checking (BMC) can be regarded as a specialisation of BIM utilisation. Practical use of BMC is like implementation of BIM influenced by a number of factors.

Germany has a tradition for "Bauinformatik" (construction informatics). This field is mostly technical and related to the development of software for engineering purposes. Interdisciplinary projects within BIM-based model checking are generally limited due to the internal structure of universities and limited research projects. BIM-related positions at universities are also still rather limited. Interdisciplinary teams with experts from construction, the law and informatics domain are not observed. The research domain within BIM based model checking is therefore rather limited. On the other hand is research within informatics, semantic technology, knowledge based engineering (KBE) well established domain. This indicate that there is established knowledge to use a foundation for specialised research within BIM based model checking

A delimited search on ITcon (2014) was done to illustrate the status of research. The Journal of Information Technology in Construction (ITcon) is a peer-reviewed scholarly journal on the use of IT in architecture, civil engineering and facility management. ITcon has close connection to CIB W78 research community. The search includes papers from 1996 to the present. A search on "Ontology" returned 25 hits, of which approximately 65% were from 2010 or later. A search on "BIM" returned 64 hits, of which approximately 70% were from 2010 or later. This indicates that the interest in these topics, or at least the use of these terms, is relatively new and increasing. A search on "model checking" did not return any hits, but one hit each was returned on "code" and on "compliance". This search does not indicate a lack of research within the topic of the thesis. IT Con searches for letters in words in papers and not the meaning or relations of words. Papers and research can therefore be relevant even if they do not give a return on the search. There are also some development within the BIM community of solutions based on use of IFC and practical case. This type of singular ad-hoc initiatives is hard to use as foundation for scientific research and methods based on principles and theories. Use of IFC and BuildingSMART is often highlighted in this type of applied research and development.

There have been a number of initiatives and the interest for BIM-based model checking is increasing. This section presents an overview of research activity within model checking. The overview is not complementary, but indicates that there is a word wide interest for the subject, but with limited extent. This study has used above research as general reference and foundation for understating of status of problems.

In Europe has the Netherlands a long research tradition within ontology based research. The Eindhoven University of technology has research group within Design & Decision Support Systems. This gives foundation for checking services. The technical aspect is covered by use of ifcOWL and mvdXML (Beetz et al., 2008 and 2011; Zhang et al., 2015). The TNO, Netherlands organisation for applied scientific research, is the driving force behind development of openBIM server solution (BIMserver, 2012). This combination is a manifestation of the strong Dutch position with theoretical and applied research. Research at Ghent University in Belgium has focus on liked data and RDF (Pauwels et al., 2011). Use of database queries using SPARQL has been highlighted in by the Centre Scientifique et Technique du Bâtiment in France (CSTB) in France (Yurchyshyna et al., 2008; Bouzidi et al., 2011).

The UK government has massive focus on digitalisation of the entire construction industry in the UK. This strategy stated development plan (UK Level 2, 2011; UK Level 3, 2015) which focus on exchange of information – from spreadsheet to use of openBIM. Use of BIM as input for compliance checking is a central part of this approach. Northumbria University (Lockley et al. 2013; Malsane et al., 2015; Nisbet et al., 2012) and Cardiff University (Kasim et al., 2013) are example of research within compliance checking process and BIM and model checking. In Norway are research at Norwegian Research Center for Computers and Law (NRCCL, 2013) the most active research community in respect of transforming legal into applicable rules for automatic og semi-automatic processing.

In USA has Professor Charles Eastman (2015) and his team at Georgia Tech School of Architecture in USA has done during a long period done comprehensive research and education related to BIM and model checking. There has been a strong focus on automation in processing of information based on open BIM / IFC. This research presents possible solution and support of technology for the future AEC industry. (Eastman et al., 2009; 2011; Solihin and Eastman, 2015).. Research within concepts for model checking is performed at University of Florida (Nawari, 2012). The Fiatech study "Proof of concept of AutoCodes" (Fiatech, 2012) can be used as an example that research and development is also performed in the industry organisations.

In Australia has the CRC for Construction Innovation developed a pilot for demonstration of practical model checking (Ding et al., 2006). There is ongoing research within automated audit of BIM at University of Auckland in New Zealand (Dimyadi, 2013). Research within legality check system has been part of the SEMUTER project at Kyung Hee University in South Korea (Chio et al., 2012).

At international level is the buildingSMART International "Regulatory Room" an very interesting initiative. This is one of five types of rooms for standard development (bSI, 2015). buildingSMART international present the purpose with this room as: "*To provide open discussion room for each government's building regulators to promote open BIM based building permission, code checking process, standards/libraries, guides and any collaborative issues. Researchers and implementers are also welcome to join*" (Kim, 2014). The invitation of researchers illustrate that this initiative is dealing with issues under development

The international CIB W78 + ICCCBE + ASCE Conference in 2014 (Issa and Flood, 2014) considered separate topics about: Automatic Approval in Construction, Decision support systems, and Knowledge management. These are broad areas and all these topics are relevant to BIM-based model checking. BIM-based model checking can therefore be regarded as a scientific topic, even if the domain has not matured sufficiently to be clearly defined and named.

## 2.2 Challenges in the AEC industry

The AEC industry plays an important role in most industrialised countries. The influence of the industry on employment and economic figures is fundamental. The environmental aspect also has an increasing focus. The AEC industry is therefore in general highly regulated in most industrialised countries.

The Norwegian Building Act consists of two parts; Planning and building (until 2014 managed by two different ministries), and runs to 66 pages. This act is supported by three codes: one for the building permit application process (34 pages), one for technical solutions (42 pages), and one on the documentation of building products (7 pages). The codes are supported with annually updated guidelines, on respectively 224 pages, 290 pages and 88 pages. The public regulations add up to 751 pages (which refer to a large number of standards). Although the regulations are extensive, the range is limited to five documents. However, the Building Acts have direct references to 15 other authorities, each with its own set of regulations (DIBK-PBL, 2014). These regulations are, of course, not harmonised. There is no dictionary of terms, or definition of most terms.

Looking into standards confirms a highly regulated industry. Some key figures from Standards Norway for standardisation in building construction and real estate, and the AEC industry are as follows:
◦ there are a total of approx. 4500 current standards relating to the AEC industry
◦ there are more than 125 ongoing standardisation projects
◦ there are more than 100 national standardisation committees
◦ the committees bring together approximately 1000 experts from the Norwegian AEC industry
◦ the industry's own efforts in the standardisation work are estimated as costing 35–40 million NOK per year (Standards Norway, 2014).

The Product and Installation department at The Norwegian Building Authority has developed a net-based service to identify relevant standards and modules of certification and has created the Byggevareinfo.no website. Byggevareinfo.no provides simple but also detailed information about why and how to build the products with the characteristics documented. The Byggevareinfo.no site is continuously updated with new standards, amendments to certification modules, and especially with new questions and answers. A search in the database on 20 December 2013 identified 416 standards related to documentation of products, and 50 hits on modules of certification (DIBK-Byggevareinfo, 2014).

The research initially had a very technology-optimistic view, aiming for all regulations to be implemented into a BIM-based model checking software. This view was supported without objections inside the limited “community of believing BIM-enthusiasts”. However, out in the “real world”, this view was often countered with questions like: “Can this regulation about …. be implemented in a BIM-based modelling software?”. The answer was often “No” or “Partly” – or that the regulations were too “blurred” or discretionary, based on professional assessment or local authority interpretation, which indicated that assessment by the local authority should be removed from the regulations. This can be regarded as going back to the increased use of prescriptive regulations. Increased digitalisation may therefore be a retrograde step for the use of function-based regulations and increased adaptation to holistic assessment (life-cycle assessment).

Instead of focusing on automatic processing as the only solution for successful digitalisation of regulations, the focus was switched from what computers can do automatically to what people can do with digitalised solutions. This enabled a new range of solutions where the focus was turned into support for people / human interpretations.

The question was therefore changed to: “Can the regulations related to a project or a building permit application be checked (or verified) by today’s solution?” The general answer, of course, was: “No”. The follow-up question was: “Do you believe that support from BIM-based model checking systems can help to improve compliance with the regulations?” – and can this contribute to the design of “better buildings”. The answer was from the professionals in the AEC industry was usually: “Yes”, followed up by a long list of proposals of what should be implemented into BIM-based model checking software.

## 2.3 Regulatory rules in commercial and public systems

A very significant difference between commercial and public systems for BMC is that commercial systems do not interpret regulations into rules. This implies that awareness of the interpretation of regulations as an independent discipline is low. Paper 7 on BMC addresses this question. Commercial developers like Solibri (2014) have only implemented part of a draft version, the DIS version of the ISO 21542:2011: “Building construction - Accessibility and usability of the built environment” standard. This version is not covered by ISO copyright properties. Only some of the prescriptive rules, mostly related to clash detection regarding turning circles, are implemented. However, public authorities can deliver machine-interpretable rules as part of their strategy for increased use of BMC in the AEC industry.

The interest from public building authorities in the development of a web-based system for the processing of building applications has gained momentum over the last year. Developments in the administration, especially digitalisation in the public sector, include some projects within the building permit applications services. Public systems for processing building permit applications are not commonly in service (Refvik, 2013). The lack of common international terms makes it hard to discover potential solutions in other countries (Hjelseth, 2013). This makes it hard to distinguish if the project is just “forms on screen” or more pervasive projects including re-development of regulations to enable cross-over information flow between the public and private sectors. The UK has developed the “Planning portal”, the UK Government's online planning and building regulations resource for England and Wales (Planning Portal, 2012). Korea is developing the SEUMTER Legality check system based on research at the Kyung-Hee University (Chio, 2012). A number of initiatives from the USA indicate the interest in digitalisation of regulations. The International Code Council in collaboration with Fiatech (2012) plays an important role in the development of computer interpretable regulations and model checking systems, of which the SMARTcode project is the best known (Conover and Lee, 2008). The “CORENET” e-Submission System in Singapore is well known (CORENET, 2012) as an example of a system which is in daily use. The Norwegian Building Authority has developed a “ByggSøk” (Building Application) launched in 2003 and still in use. This is a web-based solution for verification of completed forms relating to specific types of applications. They plan to develop a more sophisticated solution called “ByggNett” (DIBK-ByggNett, 2014).

## 2.4 Overview of software systems

The research does not focus on software or the development of software systems. However, this does not mean that the proposed systems have been developed without the implementation of software in mind. The limited focus on software must be interpreted as being because there is not just one system for implementation. It should be possible to implement the proposed systems in large numbers and using different types of software. The OpenBIM attitude, concretised by the use of IFC, will enable implementations based on a number of software systems.

Table 2 gives an overview, albeit not all-embracing, of software applicable for model checking, and illustrates how different software can be classified or divided into a limited number of main groups:

**Table 2. Overview of software categories applicable for BIM-based model checking**

| Category: | *Standard commercial software* |
|---|---|
| Buyers: | Practitioners (architects, engineers) in the AEC industry |
| Developers: | Commercial companies with a worldwide market within the AEC industry |
| Example of applications: | - Solibri Model Checker (Solibri, 2014)<br>- Autodesk Navis Works (NavisWorks, 2014)<br>- Tekla BIM sight (Tekla BIMsight, 2014) |

| Category: | *Customizable commercial software* |
|---|---|
| Buyers: | Advanced practitioners in large building projects, mostly hospital projects |
| Developers: | Commercial companies with worldwide market |
| Example of applications: | dRofus integrated program management (dRofus, 2014) |

| Category: | *Model servers* |
|---|---|
| Buyers: | Advanced practitioners in large building projects, public authorities |
| Developers: | Open source BIM collective and commercial companies with worldwide market within the AEC industry |
| Example of applications: | - Open source:<br>- Building Information Model server (BIM Server, 2014)<br>- Commercial:<br>- EDMmodelServer Jotne Technology (Jotne, 2014)<br>- EuroSTEP SABLE Server building (EuroSTEP, 2014) |

| Category: | *Rule engines* |
|---|---|
| Buyers: | So far, not identified in use in the AEC industry. Expected to be high-end solutions |
| Developers: | Commercial companies with worldwide market within all industries.<br>The AEC industry is not on the list of use cases or industries. |
| Example of applications: | - FICO Blaze Advisor (FICO, 2014)<br>- Sparkling Logic SMARTS (Sparkling Logic, 2014) |

| Category: | *Public systems* |
|---|---|
| Buyers: | National building authorities |
| Developers: | National consultancy companies – on large projects |
| Example of applications: | Developed and integrated with national regulations and adjacent standardised solutions; will normally include information from cadastre and business registry information. |

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# 3 Research approach and methodology

## 3.1 Balanced approach of theoretical and practical positions

*Focus on systematisation*

Figure 3 illustrates the research focus on systematisation. The outcome of systematisation phase is methods for specification of digital rules. The outcome of these methods is relevant both for increased knowledge and as specifications for programming. The outcome from the next phase, programming, is software code. The outcome from the last phase is change and adaptation of processes and procedures. This includes both service providers and users.

Systematisation is illustrated by three steps. The first step shows that real regulations are the starting point. Use of regulations in general and building regulations in special is supporting delimitated approach. This support an approach based on Controlled Natural Language Processing (CLP) instead of natural language processing (NLP) for interpreting of terms in, and between, regulations. The text and figures has to be structured to identify relevant elements. This has been done by use of methods, principles and tools from ontology. The outcome of these steps in systematisation will be independent of way of programming, programming method or programming language. It has been important to use a research approach that has useful outcome during the processes of systematisation. Computable rules are an intended end result, but programming and implementations is very resource intensive. Outcome of systematisation should contribute to increased understanding of the regulation – and for the AEC industry will even minor improvement be useful. Developed methods should therefore be possible to process manually or semi-automatic, support by supported by software tool as tables in word processor, structured information in spreadsheets or databases.

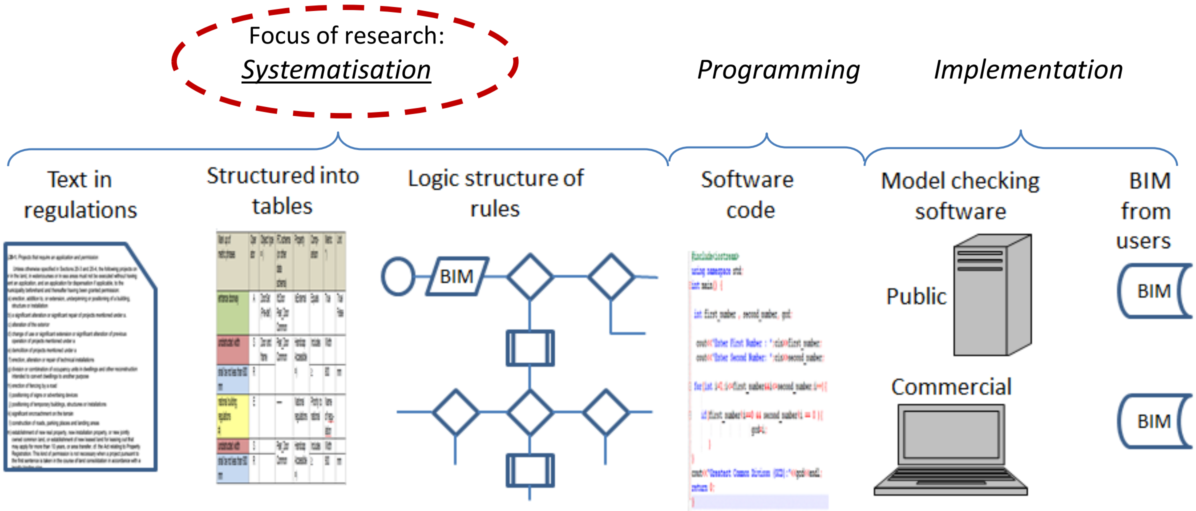


**Figure 3. Process steps in development of BMC**

*Practical constraints to support for applied systems*

The use of theory and development of methods has been done with an awareness of the desired end result: computable rule-sets in software for BIM-based model checking have been an important guiding star. Figure 3 illustrates the process steps in the development of BMC, but does not include the connections between the steps. This thesis is based on a series of papers and can therefore give the impression that BMC is a direct and straightforward process accomplished by just using the correct methods in a linear fashion. However, practical use will be influenced by cost/benefit considerations and the use of each method has to be optimised. Figure 4 shows that the stages between the steps can be dynamic, and vary between cascade (waterfall), interactive and/or iterative methods between one or more of the development steps.

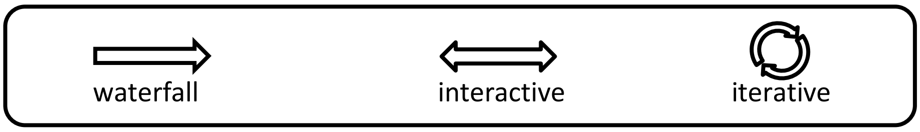


**Figure 4. Perspectives of interaction between the process steps**

The development of computable rules is challenging. Lack of experience can contribute to a need for an interactive or iterative development process. However, on well-structured regulations, and especially prescriptive regulations, the cascade method can be used to enable time- and cost-effective production of computable rules.

*Influence of industry on the primary research problem and aim*
The primary research problem focuses on how to interpret and represent normative text in a way that enables valid implementation in BIM-based model checking systems. The primary aim, based on regulations as use cases, is to develop methods for transforming text in regulations into computable code in software. This aim can be expressed as:

- *Reduction of complexity*

Interpreting regulations into applicable rules is one of the first tasks in systematisation, which is the first stage in the development of practical BMC systems. Reduction of complexity is therefore of major importance to increase understanding. This perspective is useful because it focuses on the outcome during the development process, and not only when or if the regulations are implemented into BMC.

- *Increased degree of digitalisation*

This aim indicates the industry's approach arising from the focus on the cost/benefit of the methodology, and avoiding going into the tricky problems of digitalisation through the use of resource-consuming solutions based on artificial intelligence. This implies that practical constraints like a short time and low cost for development, in addition to limited skills / knowledge in system development, has influenced the choices made during work on the papers. The proposed solutions should be suitable for use by people in the AEC industry for solving problems in that industry.

## 3.2 Case-based approach

Regulations from real codes and standards have been used throughout as cases in the research. The study focus on real and practical problems in the process of transforming regulations into computable rules in BIM-based model checking systems. Regulations can be regarded as "*normative text*" with a focus on presenting what it is allowed / not allowed to do under specified situations or constraints. The developed methods are, of course, applicable for all types of text, not only regulations. The methods should therefore work well for other requirements such as a company's quality specification or to check if a company's solutions/specifications are being used by sub-contractors or suppliers. It is not the result on the regulation that has been in focus, but the validity of developed methods. In principle could any normative text be used to explore developed methods. To illustrate that the methods is not dependent on specific documents has a variety of real regulations are use as cases to explore the developed methods. The overview of case studies are therefore listed after method to illustrate that use of real cases has been in exploring practical use of the methods.

- *RASE methodology*

RASE is an abbreviation for requirement (R), applicabilities (A), selection (S) and exceptions (E).
The RASE methodology has been tested on following three categories of regulations; standards, codes, and guidelines.

-- *Standards*
The case was based on NS 11001-1.E:2009 “Universal design of building constructions - Part 1: Work buildings and buildings open to the public”( NS 11001-1.E:2009). This Norwegian standard is available in an English version.
-- *Codes*
The case was based on ICC IECC 2006 502.5 “Moisture control” from International Energy Conservation Code by International Code Council, Inc in USA. (ICC, 2006). This code has a tabularised presentation
-- *Guidelines*
The case was based on Chapter 3 in the Planning for U.S. Courthouse from US Courts design Guide by U.S. General Service Administration (GSA) (GSA 2011). Guidance documents may not undergo the intensity of review and revision applied to regulatory documents.

The experiences indicate that the RASE methodology can operate on a different types of normative documents with a trustworthy results.

More information about the study is presented in paper 2 and 4.

- *Tx3 methodology*
The Tx3 methodology (Transcribe / Transform / Transfer) is designed for assessing degree of automatic checking of regulations. This method has been explored by use of ISO21542:2011 “Building construction - Accessibility and usability of the built environment” (ISO21542:2011). The standard is rather new, 2011, and includes both function bases and prescriptive requirements. This type of standards, and this standard in special, is a very good candidate for BIM-based model checking. The complete version of this standard was used to illustrate that the practical value of this method is when on can use this as support for planning a rule development project. The 152 pages are divided into 42 clauses. Each clause and sub-clause was spit up into 680 unique requirements. Each requirement – now identified as unique rule was then classified according the Tx3 criteria for Transcribe, Transform or Transfer. The result of this was organised into a table (spreadsheet) which identified on clause level different degree on each clause and the entire standard. This type of outcome is relevant of set the expectation and to give priority to which clauses that are most applicable for development into computable rules – in advance of programming. More information about the study is presented in paper 5.

To illustrate the impact of this standard was a survey of requirements which has been implemented into model checking software explored. This survey was based on the BIM delivery requirements from Statsbygg, Norwegian Public Construction and Property Management Agency. Statsbygg have developed BIM-guidelines since 2008, and the current version, 1.2, is the third and is available in both Norwegian and English versions (Statsbygg 2013). The BIM-guidance document contains 131 requirements which were classified according to the three categories in Tx3 methodology. The requirements includes as rule set in Solibri Model Checker software (Solibri, 2014). More information about the study is presented in paper 6.

- *TIO methodology*
The TIO methodology (Test Indicator Objectives) can be used to increase the degree of computable rules was used. This method supplement rules classified as “Transform” by the Tx3” methodology.
The ISO21542:2011 presented in “Building construction - Accessibility and usability of the built environment” (ISO21542:2011)Use of TIOA resulted in increased degree of computable rules. More information about the study is presented in paper 5.

*- Ontology engineering*
Study of ontology based approach for increased understanding and simplification of regulations was done by use English version of the fire regulations in the "Norwegian building code for technical requirements" (TEK10, 2010) and belonging Guidelines for the technical requirements (V-TEK10 2013). Use of a both code and guideline represent practical use – both must be used – and this enabled to see the compatibility between the documents. The fire safety section in the code covers 7 of 37 pages, and 75 of the 303 pages in the guidelines, or approximately 10 times as many pages as the code. This can indicate that this topic is complicated and contains detailed requirements. In addition, the regulations refer to other legislations and standards. More information about the study is presented in paper 7.

*- Software*
Relevance for the industry is a relevant perspective for this PhD study. An overview of available software was overview was presented. The software was grouted into commercial and free version of software. The software was selected on general use in the AEC industry. The purpose was not to give a complete overview, because the will be changes in software, but to illustrate that it is possible to compare BMC software in a systematic way. This can be used to select relevant software related purose. More information about the study is presented in paper 6.

*- User experience and expectations*
In relation to a study about BIM-based model checking was depth interviews included. The informant was representing companies with the-state-of-the-art profile in utilization of BIM and BMC. All companies are among the largest in their branch of the construction industry in Norway .selected BIM experts / BIM manger in state-of-the art BIM projects and organisation with high profile on use of BIM. The informants represented public serial owners, public builders, architects, consulting engineers, contractors and property developers. The selection of informants is by no mean not representative for the average in the AEC industry, but to give examples from all branches in the industry. All informants received a questionnaire with questions in five groups. This was followed up by a depth interview by telephone. All informants were informed that the questionnaire and interview would be presented anonymously. More information about the study is presented in paper 6.

## 3.3 Multi-disciplinary approach

The multi-disciplinary approach influences both understanding of the research problem and the development of applicable methods. The multi-disciplinary approach can be characterized by:

- regulations interpreted within a limited domain or known context (legal aspect),
- the use of BIM and semantic methods (informatics perspective), and
- the priority of simplicity in methods that can be used without major investment (construction perspective).

Every professional and scientific domain has a different view on what the problem is and how it can be solved. A common denominator for the single domain view is that all problems can be solved with more advanced and sophisticated solutions. This approach is hardly applicable for the AEC industry with its large number of regulations and requirements, low capacity to invest and generally low level of digital solutions. The multi-disciplinary approach is based on an integrated approach involving interaction between the legal, informatics and construction domains. This concept is here called the "L+I+C approach" (Hjelseth, 2013), where L = Legal domain, I = Informatics domain and C = Construction domain (includes all discipline in the AEC industry). Exploring these three domains starts by taking single domain view and expanding this to dual approach. This can be further integrated into the triple domain view of integration, as illustrated in Figure 5.

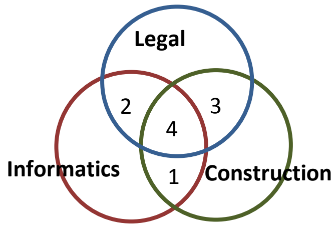


**Figure 5. Model of integrated approach for model checking systems**

The intersections can be expressed as follows:

- Intersection 1 — BIM can be regarded as interactions between construction and informatics
  - Examples: "Clash detection" based on geometry
- Intersection 2 — Ontology can be regarded as interactions between informatics and the legal domain
  - Examples: Coherent interpreting thoroughly or between regulations
- Intersection 3 — Constraints of rules can be regarded as interactions between the legal and construction domains
  - Examples: Connection between type in regulation and instances in construction.
- Intersection 4 — Integrated approach – holistic view
  - Examples: Practical checking Automatic building application and permission systems

## 3.4 Contribution from natural language processing (NLP) and controlled natural language processing (CNL)

The research has an applied focus enabled by the combination of selected perspectives from established theories instead of specialisation with one theory. As presented in section "1.5 Overview of theoretical perspectives" is the research based on specialisation of approaches based on ontology and processing of language. To illustrate this specialised perspective is contribution from language processing presented first, and the more general ontology presented in next section. This approach implies that the research is based on a specialised view – and the outcome of this study can be regarded on a highly specialized domain: interpreting normative text into rule-based systems. This specialised use of theories is intended to contribute to more applicable methods instead of more theory.

The intention with this section is therefore give general background of CNL and how this influence the way of thinking and working in the study. It will therefore not be a presentation of specific CNL theories / theory directions ("schools") or methods used directly in development the methods presented in this thesis. Use of CNL contributes to focus method to be applicable within a defined domain like national building regulations, defined standards etc.  Use of established solutions in the AEC industry like IDMs for specification of exchanged information (IDMs are based on the ISO 29481 series of standards). This system will establish a constraint witch support use of CNL rather than an approach based on NLP.

There is also a bidirectional relation between ontology for interpretation of text or terms in (relatively) known context. Model checking will be performed within a limited domain, a limited set of documents involved for – and with delivery of information based on defined schemas IFC with specified entities and attributes (property sets) defined in ISO 16739:2013 or never. Extensions of this schema will be used by use of data dictionaries, in practice the buildingSMART Data Dictionary, following the ontology based ISO 12006-3 standard.

Natural language processing (NLP) is described by Chowdhury (2003) as an area of research and application that explores how computers can be used to understand and manipulate natural language text or speech to do useful things. In this respect, interpreting building regulations must be regarded as useful. Based on this, just implementing NLP seems to be enough to solve the problem. However, the situation is not so simple. Liddy (2001) characterises NLP as a computerised approach for analysing text. This approach is based on both a set of theories and a set of technologies. NLP is a very active area of research and development, where there is not a single agreed-upon definition that satisfies everyone.

In Wikipedia, NLP is described as a field of computer science, artificial intelligence, and linguistics concerned with the interactions between computers and human (natural) languages. As such, NLP is related to the area of human–computer interaction. Many of the challenges in NLP involve natural language understanding, that is, enabling computers to derive meaning from human or natural language input, while others involve natural language generation (NLP, 2014).

This explanation from Wikipedia presents NLP as a multi-disciplinary domain. This approach corresponds with the approach used in this thesis. However, the research scope focuses on regulations within the AEC industry. This implies that the type or text only has to be understood with a specified category and the vocabulary is limited. Tarski (1935) states that within a limited domain the processing of language should be possible, but including the whole word is not possible. One may use NLP for common understanding, but interpreting regulations requires high precision to be trustworthy. An example of this is given by Sowa (2000), who refers to the Halo project in which an attempt was made to represent the knowledge in a chemistry book in an AI system. The results were a score of only 40–47 % correct at a cost of about $ 10,000 per page of the textbook. This experiment indicates that NLP in general will not be a realistic solution for interpreting text in regulations. A chemistry text book as an explanatory text is highly influenced by the style of the author, whereas a regulation can be regarded as normative text written to express a statement of constraints under specified conditions or contexts.

Sowa (2006) mentions the heterogeneity of the chemistry text as one explanation that led to what is termed “knowledge soup”. The “knowledge soup” arose for four reasons: a) overgeneralisations, b) incomplete definitions, c) conflicting defaults, and d) unanticipated applications. Sowa further notices that experience shows that these exceptions and borderline cases result from the nature of the world, not from language or logic (ibid.).The focus of research has therefore turned to controlled natural languages (CNLs). CNLs are subsets of natural languages, obtained by restricting the grammar and vocabulary in order to reduce or eliminate ambiguity and complexity. Traditionally, controlled languages fall into two major types: those that improve readability for human readers (e.g. non-native speakers), and those that enable reliable automatic semantic analysis of the language.

The first type of language (often called "simplified" or "technical" language), for example, ASD Simplified Technical English, Caterpillar Technical English, and IBM's Easy English, is used in industry to increase the quality of technical documentation, and ideally simplify the (semi-)automatic translation of the documentation. These languages restrict the writer with general rules such as "Keep sentences short", "Avoid use of pronouns", "Only use dictionary-approved words", and "Use only the active voice". Use of the buildingSMART DataDictionary (bSDD / IFD) can be regarded as an example within the AEC industry of this type of language. bSDD can be used to support dynamic extension of BuildingSMART DataModel (bSDM / IFC), which contains around 700 entities, or basic terms. This enables mapping to the bSDM / IFC from multiple sources. TIO, Test Indicator Objectives, is a methodology developed in this study that uses this type of approach. This methodology is explained in more detail in chapter 5.4.

The second type of language has a formal logical basis, i.e. with a formal syntax and semantics, and can be mapped to an existing formal language, such as first-order logic. Thus, these languages can be used as knowledge-representation languages, and the writing of those languages is supported by fully automatic consistency and redundancy checks, query answering, etc.
The linked data approach and use of a Resource Description Framework (RDF) is based on this type of language. Use of this approach is included in paper 7 on "Trustworthy interpretation of normative text by use of ontology". The presentation of different theories of language processing indicates that there are established highly specialised methods. For solving practical problems a combination of both languages can be used to achieve the most acceptable results within a limited time and cost.

The RASE methodology (Requirement, Applicability, Selection and Exceptions) is one of the outcomes of this research. This can be regarded as a specialised language for processing regulations – and can be described as "rulish". The name "Rulish" was introduced in presentations to illustrate that regulations resented as rules had to be written, and read, differently from linear presentation of text and numbers in ordinary regulations. Restructuring into tables and use of diagrams of "boxes and arrows" was used to illustrate that normal left to right reading could be supplemented by more dynamic language. Regulations presented as "rulish" should be possible to be understood by professionals in the legal and construction disciplines.

## 3.5 Contribution of ontology

Regulations and standards are collections of words. These words describe an action – what to do in which way by whom under specified conditions. A focus on the ontology of regulations is therefore an integrated part of this study to enable systematic interpretation of text and terms in context.

As explained in previous section about CNL, there is no single theory or branch ("schools") of ontology that are used or tested in development of in this thesis. Focus is more on how ontology can make it applicable to work systematically with language related issues for interpretation of text / terms in context in a systematic way. This observation can appear as obvious. However, based on systems that should have a complete range defined terms – like legislation, it is hard to observe that this is the case. Standards have "terms and definitions" as a mandatory clause, but definitions are limited and each standard can make their own definitions. Regarding input of information in model checking will use of ontology based solution like BuildingSMART Data Dictionary enable. However, based on the situation in the AEC industry and use of BIM, solutions which is easy to implement is preferable than solution that at are ideal, but hard to implement. This implies that proposed methods in this thesis are relatively simple, but can be scalable by use or more advanced ontological methods and semantic technology.

Ontology can be regarded as a concept for shared understanding, which focuses on "what it is" and not only on "what it is called". According to Gruber (1993), ontology is defined as the formal specification of a shared conceptualisation. The use of ontology engineering has been presented by Beetz et al. (2008) "as a way of transforming understanding". The roles of ontology vary from knowledge management to semantic interoperability. The intention is to present methods and examples where an ontological approach contributes to the increase of shared understanding by using simple methods and examples based on regulations used in the AEC/FM industry (by architects, engineers, contractors/facility management). The AEC industry is about the design, building, and maintenance of physical objects like buildings, bridges, roads, railways, etc. These constructions can be visualised through drawings and models, both as physical scale models and visual virtual 3-D models, in addition to building information models (BIM). BIM has the capacity to integrate visual representation with information in text and values.

In computer science and information science, ontology formally represents knowledge as a hierarchy of concepts within a domain, using a shared vocabulary to denote the types, properties and interrelationships of those concepts (Ontology, 2014). This study focuses on systematisation and not on programming and implementation. This implies that the direct use of semantic technology and of software is not highlighted. On the other hand, an awareness of professional semantic theories and methods is important because it will enable preparations for practical implementations. Ontology engineering can be used as a key word for this approach. Pouchard et al. (2000) explain as this as: "Ontology engineering aims at making explicit the knowledge contained within software applications, and within enterprises and business procedures for a particular domain." Ontology and the semantic approach are of increased interest in construction-related research. Initiatives like Linked Data in Architecture and Construction (LDAC, 2014) indicate that there is research within this domain to solve problems for digital solutions applicable in the AEC industry. Use of Resource Description Framework (RDF, 2013) can enable semantic search through multiple regulation documents. In development of terminology for a joint vocabulary can Semantics of Business Vocabulary and Rules (SBVR, 2014) be an interesting methodology to explore. Ontology is a well-established research domain within informatics. Ongoing research projects to develop ifcOWL within the BIM and buildingSMART community can support the establishment of semantic-based methods as a default (Krahtova et al., 2013). As an indication of the strong focus on interoperability, buildingSMART was originally called the International Alliance for Interoperability (IAI).

The European Interoperability Framework (EIF, 2011) defines four levels of interoperability – legal, organisational, semantic and technical – that should be taken into account, presented in Table 3.

**Table 3. The four levels of interoperability (EIF, 2011)**

| Level of interoperability | Alignment | Description |
|---|---|---|
| Legal interoperability | Legislative alignment | Aligned legislation so that exchanged data is accorded proper legal weight |
| Organisational interoperability | Organisation and process alignment | Coordinated processes in which different organisations achieve a previously agreed and mutually beneficial goal |
| Semantic interoperability | Semantic alignment | Precise meaning of exchanged information which is preserved and understood by all parties |
| Technical interoperability | Interaction & transport | Planning of technical Issues involved in linking computer systems and services |

Use of openBIM can be regarded as another constraint in use of BIM as the input of information for model checking. Open BIM will in practice be IFC files. The IFC-schema (ISO 16739:2013) contains a limited number of entities, approximately 700, that will be used for mapping and transferring information. The use of related property sets (Pset) contributes to including all relevant attributes. Support from a data dictionary such as bSDD (BuildingSMART Data dictionary (ISO 12006-3:2007) can contribute to dynamic extensions of attributes. The use of real regulations (normative text) intended for implementation into BMC (based on IFC) gives a framework for applicable solutions that contributes to reducing complexity.

## 3.6 Ethical concerns

The research has its focus on the development of methods. The development process itself has limited ethical concerns. Paper number 7 includes in-depth interviews, but these are presented anonymously.

However, the impact of the implemented solutions from the research must be subject to ethical concerns. These aspects are discussed within the legal domain, together with methods for identifying relevant questions and possible solutions (Schartum, 2011). The ethical aspects cover a number of subjects, from the power of judgments in automatic processing to concerns about privacy and sharing of information. Ethical concerns may also influence how future regulations become developed, and influence the use of technology, especially BIM.  This study does not include implementation in BIM-based model checking (BMC) systems. Development and implementations of computable rules should include ethical concerns.

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# 4 Results from papers

Below are the summaries of the results of seven papers published in scientific journals and presented at conferences. The order of the papers is in a timeline from the first paper in 2009 to the last paper submitted in 2013, accepted in 2014 and published in 2015. All reviews are presented with a short overview and a presentation of what is in focus as the research problem in the paper. The “Findings and proposed solutions” section includes a short overview of the proposed methods. The last section on the “Contribution to further studies” indicates how this paper has contributed in the continuation of the PhD study.

The complete versions of all seven papers are presented in Annex A.

## 4.1 Paper 1: Overview of concepts for model checking

***Overview and focus***

This paper was presented at the industry session of the CIB-W078 Conference in Cairo, Egypt, 16$^{th}$ – 19$^{th}$ October 2010. Nick Nisbet from ACE3 Ltd. in the UK was co-author.

Model checking is a widely used term, but without any clear definition or joint understanding. Model checking is often used synonymously with clash detection or compliance checking. The intention in this paper was to use an ontology-based approach to analyse the term and to contribute to a better understanding of the principles of model checking.

***Findings and proposed solutions***

This paper presents an overview of concepts of model checking. This has resulted in a description of four different concepts based on the intention of checking. These four concepts of model checking are summarised in Table 4.

**Table 4. Concepts of model checking**

| Intention | Result |
|---|---|
| Validating: | pass/fail |
| Guiding: | options and advice |
| Adaptive: | a modified model |
| Content: | a filtered norm |

An often used example of model checking is clash detection to validate if, for example, different types of pipes intersect each other. Another example is checking if the width of doors is according to codes of accessibility. However, there is a common perception that model checking is only about validation and yes/no answers. This paper broadens model checking in a systematic way and ends up with four unique concepts.

The proposed taxonomy for model checking can be seen as a contribution to the more precise use of model checking. This approach makes model checking part of a knowledge system. The full range of model checking concepts can be regarded as a framework for the utilisation of existing “knowledge systems”. The use of this must support the focus on doing the right things – and doing the thing right. To do this, a number of approaches have to be used. Different concepts of model checking (not only validating) can be combined. There is reason to assume that too much validation and code compliance can be counterproductive with respect to the development of new ideas and solutions for the built environment. Supplementary concepts with other intentions, especially guidance, should be explored.

- *Validating model checking*
The purpose of validating checking is to determine if the technical solutions in the model are in accordance with a code, standard, regulation, etc. Validating model checking is performed based on predefined criteria and results in a yes/no answer. Clash detection is geometry-based checking and is maybe the most well-known use of checking. This type of checking is very useful and is often included as part of the quality assessment (QA) system when merging models in interdisciplinary projects.

Some examples of compliance checking can be to identify:
- intersections between predefined objects, like air shafts or water pipes and beams or walls
- if the wall requires a defined "opening in wall" for other components
- doublets of components due to errors of under-drawing, e.g. two identical windows in the same location

- *Guiding model checking*
The intention with this concept is to guide the designer to consider a larger range of realistic solutions than is practical without this support. It is particularly relevant in areas where the designer is not expert or experienced. Best practice rules can be embedded as part of this concept.

- *Adaptive model checking*
The intention here is to let the object ("technical solution") itself register its environment and adapt automatically to this by following embedded pre-defined rules. The design process is dynamic and it is therefore a big challenge to adjust all the technical solutions – presented as objects - after an update. This concept of model checking will often be very useful in areas/domains where you are not the expert. There are two levels of adaptive model checking: object and system level.

- *Model content checking*
The intention here is to examine the professional content in a BIM model for a specified use. There is no need for programming complex rules, just "filters" for reporting relevant information. This can be further analysed in software such as spreadsheets, word processors or databases. This gives this concept great flexibility for practical use. Today this can be done very easily and manually by model viewers, or with more complexity by using model servers. User-friendly solutions are needed.

***Contribution to further studies***
The outcome contributes to broadening the scope of model checking to include more than validation or compliance checking based on clash detection. This paper illustrates the importance of solid foundation development of methods and precise use of terms. The use of ontology and the need to construct taxonomies have been used in most of the following papers. This paper prepares for a systematic approach to structuring rule checking systems. The next paper follows this with the development of a semantic-based method for BIM-based model checking.

## 4.2 Paper 2: Exploring semantic-based model checking

***Overview and focus***

This paper was presented at the industry session of the CIB-W078 Conference in Cairo, Egypt, 16th – 19th October 2010. Nick Nisbet from ACE3 Ltd. in the UK was co-author.

This paper intended to explore the foundation of semantic-based model checking concepts. Semantic-based model checking has the potential to radically alter the cost/benefit balance for model checking tools. The use of semantic mark-up methods shows the importance of having a solid scientific basis. This is very important if one is going to scale up the use, or more important, if model checking is used for formal verifications.

***Findings and proposed solutions***

The outcome of this paper is scientific documentation of the RASE methodology. Rules can be directly specified from the text by using four semantic mark-up operators: Requirement, Applicability, Selection and Exceptions. This study demonstrates that this classification of text (in regulations) can be done by AEC professionals. This has often been done by programming experts. The connection between marked up text and the generation of applicable software code is direct. This paper does not describe a complete model checking system, but verifies principles as a foundation for practical use. This approach represents a shift from the "ad-hoc" methods where problems are solved during the programming process. The theories that are used in
Logic in the sematic RASE methodology is related to Boolean operators. Validation of input can be supported by use of a constraint model. Use of RASE methodology on a regulation about moisture control is demonstrated. The RASE methodology contributes to reducing complexity and establishing a foundation for further programming and implementation.

The relation between the operators and the original building codes in text is made apparent by a colour system according to the mark-up language. An example of the mark-up operators and the related colours in software is given in Figure 11 and 12 in chapter 5.2 on "RASE – Requirement, Applicability, Selection and Exceptions".

***Contribution to further studies***

This paper is used as the theoretical foundation for the RASE methodology. This paper is relatively theoretical in its mode of argumentation. The following CIB W078 paper, "Capturing normative constraints by use of the semantic mark-up RASE methodology", (paper 4) indicates that RASE is working in practice, while this paper indicates that it works in theory. This is important for developing large-scale solutions.

## 4.3 Paper 3: Exchange of relevant information in BIM objects defined by the role- and life-cycle information Model (RIM/LIM)

***Overview and focus***

This paper was published in a special issue on Integrated Design and Delivery Solutions (November 2010) of the Architectural Engineering and Design Management journal. The background for this paper was an invitation from Professor Matthijs Prins at Delft University of Technology, based on the presentation of a conference paper on the first Integrated Design Delivery Solution in Espoo in Finland in 2009. IDS has since then been updated to IDDS, Integrated Design Delivery Solution.

This paper focuses on how to specify relevant content of information in objects and object libraries for the exchange of relevant and reliable information in BIM-based software. The lack of defined information in model objects in BIM-based software limits the utilisation of information in the design process in general and IDDS in particular. The limited content of information objects (object libraries) is connected with the lack of consensus about what type of information should be exchanged.

***Findings and proposed solutions***

The proposed “Role- and Life-cycle Information Model” (RIM/LIM) can be used as a framework for specifying the relevant information in BIM objects according to its use in different roles and phases of the life-cycle. The RIM/LIM represents a cross-over solution and has references to the IDDS concept for interaction between people, process and technology.

The previously described RIM and LIM framework can be combined into an interlinked "Role- and Life-cycle Information Model" (RIM/LIM) framework for development of the specification of content in the BIM objects. In contradiction to the “enrichment of the model”, where more information is synonymous with better, leading to information overload, the RIM/LIM focuses on the relevance of information in relation to the purpose.

Paper 3 presents the RIM/LIM framework which defines the mandatory information for a defined type of object for a defined stage and role in the building process. Content in BIM objects can be included as specifications in IDMs (Information Delivery Manuals) and BIM guides. Other use cases, such as approvals, warranty tracking and maintenance procedures, can be added to ensure compatibility with COBie (Construction Operation of Buildings information exchange).

***Contribution to further studies***

The principle from this paper is about the specification of relevant information. Roles and life-cycle stages are used as a framework specification of relevant information. This aspect is widely used in later papers in the PhD study – often presented with awareness of “*the I in the BIM*”. This paper has also been used as the foundation for “Modular BIM guidelines” presented at the CIB-W078 Conference in Sophia-Antipolis, France on 23–26 October 2011. This conference paper is not a part of this PhD thesis. The focus on roles and content of information is followed up in paper 6 on “BIM-based model checking (BMC)” to illustrate the awareness of process in the development and use of BMC.

## 4.4 Paper 4: Capturing normative constraints by use of the semantic mark-up RASE methodology

***Overview and focus***

This paper was presented at the industry session of the CIB-W078 Conference in Sophia-Antipolis, France on 23rd –26th October 2011. Nick Nisbet from ACE3 Ltd. in the UK was co-author. It follows up the preceding year's CIB W078 paper "Exploring semantic-based model checking" with experiences from practical use on regulations. Structuring regulation into computable rules must be a practical "production". This paper intends to demonstrate the use of the RASE methodology in practice on a variety of normative documents. The RASE method use four operators to mark-up the text with different colours representing: Requirement (blue), Applies (green), Selection (red) and Exceptions (orange).

***Findings and proposed solutions***

The RASE methodology has been tested on the following three categories of documents:

- text in standards (case: NS 11001-1.E:2009 Universal design of building constructions - Part 1: Work buildings and buildings open to the public),
- standards with tables (case: Dubai regulations), and
- guidelines (case: GSA court design guidance document, USA).

The results indicate that the RASE methodology can operate on different types of normative documents with trustworthy results. The experience for this study indicates that relevant information from the regulations can be captured as rules for model checking in a time- and cost-effective way.

***Contribution to further studies***

This paper shows through practical cases that the RASE methodology can contribute to significant improvements in terms of reduced time and documentation for capturing requirements. The use of mark-up to capture simple metadata gives a foundation for both automatic and user-driven model checking systems. The methodology also exposes the fundamental metric phrases which a building model server or user must answer during automatic or interactive model compliance checking. This observation is followed up in the next paper (5), where the method's degree of digitalisation is explored in practice on a complete version of a standard.

## 4.5 Paper 5: Experiences on converting interpretative regulations into computable rules

***Overview and focus***

This paper was presented at the CIB-W078 Conference in Beirut, Lebanon on 17th –19th October 2012. It follows up the “Converting performance-based regulations into computable rules in BIM-based model checking software” paper presented at the ECPPM 2012 Conference in Reykjavik (Hjelseth 2012a).

The intention in this paper is to explore methods for the determination of digitalisation, and solutions to increase the degree of digitalisation of regulations into computable rules in BIM-based model checking systems. The study was based on the ISO 21542:2011 “Building construction -- Accessibility and usability of the built environment” standard.

The Tx3 methodology is based on classification of the structure of regulatory statements into three main categories: Transcribe, Transform and Transfer. This method contributes to determining the degree of digitalisation of regulations.

The “Test Indicator Objectives” (TIO) is a methodology for transforming (mapping) qualitative goals in the regulations into discrete metrics for enabling automatic model checking. This method enables an increased degree of digitalisation by interpretations of qualitative requirements in the regulations into quantitative values in the rules

***Findings and proposed solutions***

The outcome of this study indicates that the proposed methods, Tx3 and TIO, are applicable. In addition to scientific output, the experience from working with this study indicates that the methods are applicable for practical use in terms of time- and cost-effective development. The study was performed on the complete version of the ISO 21542:2011 “Building construction -- Accessibility and usability of the built environment” standard.

*Determination of degree of digitalisation of regulations*

Exploration of the ISO21542 standard identified a total of 680 rules, of which approximately 57 % were classified as Transcribe and could be directly implemented as computable rules in software. 17 % of the statements in the standard were expressed as discretionary, and need a general professional assessment to be interpreted. 26% of the regulations were expressed in such a way that under-defined situations could be defined with quantitative measurements. These should be convertible into rules applicable for BIM-based model checking. These regulations were processed further by using the TIO methodology.

*Increased degree of digitalisation*

The impact of the “Test Indicator Objectives” (TIO) as a methodology for transforming (mapping) qualitative goals in the regulations into discrete metrics for enabling automatic model checking is illustrated in Figure 6.

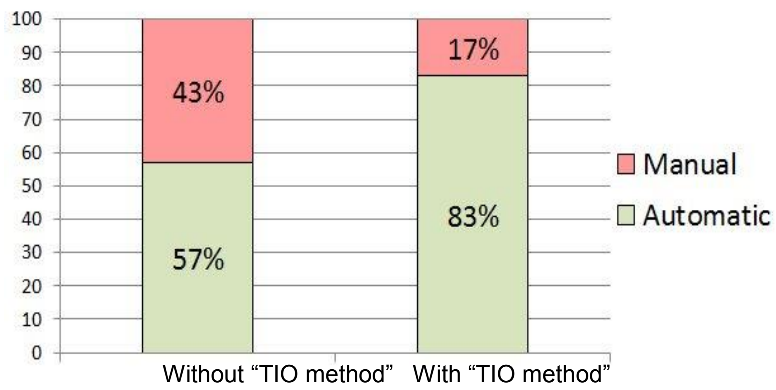


**Figure 6. Effects of the TIO methodology on model checking**

The impact of verification of accessibility is that the number of rules that have to be checked manually is reduced by 26%, from 43% to 17% of the total number of rules. Even if these results are related to only one standard, the outcomes indicate that manual interpretation can be reduced to a level where the amount of manual checking will be manageable. A flowchart was used to illustrate the combination of these two methods.

The outcome and experiences from the use of the Tx3 methodology and the TIO methodology indicate that they are applicable for practical use. The user experience from work with this paper indicated that this approach was time- and cost-effective. However, increased use of dedicated software solutions would have improved the “production” processes of computable rules. Working with the complete standard, resulting in the identification of 680 rules, should be supported by the use of dedicated software to increase efficiency.

***Contribution to further studies***

This and previous paper focused on the development of theoretical foundations for exploring applicable methods. The next two papers follow this up by exploring combinations of different methods and processes. The perspective of next paper: “BIM-based model checking (BMC)” (paper 6) has a focus on the processes and all the elements that have to be aligned to enable increased quality in model checking. The last paper: “Trustworthy interpretation of normative text by use of ontology” (paper 7) focuses on the presentation of ontology based on a series of methods that could contribute to an increased understanding interpretation of regulations to support specifications or rules.

## 4.6 Paper 6: BIM-based model checking (BMC)

***Overview and focus***

This paper was a follow-up on an invitation from Professor Raymond Issa at the University of Florida for chapter in an anthology about “Building Information Modeling: Applications and Practices in the AEC Industry”. The anthology will be published winter 2015 by the American Society of Civil Engineers.

This paper is about BIM-based model checking (BMC). BMC is often referred to as one of the major benefits in utilising BIM, where everyone can perform compliance checking and design coordination. Wide use of BMC software in BIM-based projects should therefore be expected. This paper explores the current status and challenges for increased utilisation.

***Findings and proposed solutions***

This study is based on a broad approach, ranging from exploring the principles of model checking to practices in state-of-the-art companies, in addition to reviewing commercial software. The outcomes indicate that functionality in commercial software covers requirements for model checking in projects based on the use of simple rules and unspecified content of information in the BIM file. Improved collaboration based on coordinating merged BIM files and automatic clash detection was regarded as the main benefit of model checking. BMC was regarded as a part of company quality assurance systems for model coordination. Wide use of BMC was not observed and the use of BMC software was regarded as a specialist tool, normally operated by one or two users, also in the largest projects. This study indicates the potential for further development of rule-sets and procedures for trustworthy compliance checking. In this respect, BMC can be regarded as a catalyst for the exchange of high-quality BIM for cross-disciplinary collaboration. Utilisation of BMC can be used as an indicator of BIM maturity.

This study intends to present the principles of BIM-based model checking (BMC). The components in a BMC system consist of three parts:

- Information in the BIM file
- Logic in the rule-set
- Function in the model checking software

- The quality of the BIM file, measured as the structure and content of relevant information, is of great importance for trustworthy model checking. This must comply with requirements in the rule to avoid the so-called “garbage in – garbage out” syndrome. BIM guidance and similar specification of content in the BIM file can be used to address the specification of information.
- Rule-sets are collections of rules within one topic, such as BIM validation (clash detection), space validation, model version comparison, comparing the structural versus architectural model, MEP solutions, and content of information in the BIM files.
- Software includes the service- and function-enabling import of BIM files, processing of rules, and presentation of results. User-friendliness and other features like visualisation of issues and reporting tools are part of the software performance.

Another finding from this study was the lack of a common understanding of BMC. This study therefore includes a proposal for a framework for classification for BMC, as presented in Figure 7.

Content of information "I in the BIM"

| | | |
|---|---|---|
| **Specific purpose checking** Standard software. Adding specified values to existing properties in BIM objects. Advanced content checking. ***Level 3*** | **Integrated model checking** Adding values according to specifications in new properties in BIM objects. Advanced content checking. ***Level 4*** | **Pervasive model checking** BIM of multiple integrated models. Compliance checking with wide scope. Dedicated rule-sets. Replace manual checking. ***Level 5*** |
| **Adjusted model checking** Standard software. Adding values for existing properties in BIM objects. ***Level 2*** | **Specific purpose checking** Compliance checking of specified scopes. Compliance checking of dedicated domains. ***Level 3*** | **Integrated model checking** Adding new properties and values according to specifications of new BIM objects. ***Level 4*** |
| **Clash detection checking** Standard software. Geometric checking of interference. Default values, no adding of values to properties. Support manual checking. ***Level 1*** | **Adjusted model checking** Standard software. Adding values according to specifications in existing properties in BIM objects. ***Level 2*** | **Specific purpose checking** Guidance. Standard software. Adding new properties with values to relevant BIM objects. ***Level 3*** |

Complexity of digital rules

**Figure 7. Classification of BMC levels for compliance and content checking**

The taxonomy for classification of the level of BMC compliance and content checking is based on two criteria (taxa):

- requirement of content of information in the BIM file ("the I in the BIM")
- complexity in the rules/rule-set (intelligence of rules).

The complete version of the paper is presented in Annex A for more information.

***Contribution to further studies***

The contribution to further studies can be divided into two parts:

The first part is to understand the development of BMC solutions as interactions between software, the structure and content of relevant information in the BIM file, and applicable rule-sets in the software solutions. All these elements must work together to develop rule-sets for practical use.

The second part is the need to use the framework for classification of the level of BMC for joint understanding, which is very important for further studies. Without a joint framework for joint understanding, it will be very hard to assess whether other studies and developments are relevant for one's own situation or not.

## 4.7 Paper 7: Trustworthy interpretation of normative text by use of ontology

***Overview and focus***

This paper, like the previous one, was a follow-up on an invitation from Professor Raymond Issa at the University of Florida for an anthology about "Ontology in the AEC domain: A decade of research and developments". The anthology will be published winter 2015 by the American Society of Civil Engineers.

The intention of this paper was to give examples of the practical use of ontology-based methods to improve the interpretation of regulations and to prepare for implementation into BIM-based model checking systems. The English text version of the fire regulations in the Norwegian code "Regulations on technical requirements for building works" (TEK10 code) was used to ensure transparency and reliability.

***Findings and proposed solutions***

This study explored multiple ontology-based methods: terminology was explored by means of using the Semantics of Business Vocabulary and Rules (SBVR, 2014). Various uses of the Resource Description Framework (RDF) were presented for development of a shared vocabulary and identification of relevant information. Methods for the restructuring of regulations and extracting relevant information were explored.

Experiences from real case used in this study indicate that the explored methods and frameworks can be applicable for practitioners. Positive outcomes can be achieved after interpreting a limited amount of text, as part of regulations, standards, or contracts. Increased use of the ontology-based method can result in significant improvement in the practical interpretation of regulations supported by digital services.

This summary seeks to underline three aspects of ontology in the use of:

- question- or rule-based methods for joint understanding of terms
- shared vocabulary enabled by linked data for obtaining the relation between relevant terms
- taxonomy to re-structure lists of types, explained by hazard classes in the TEK10 code.

*- Question- or rule-based methods for joint understanding of terms*

The traditional way to establish joint understanding is to write a definition based on consensus about a text that defines the term. This process often includes long discussions and interpretations of terms in the definition text. Another approach is to develop a joint understanding based on questions or statements. One can thus gain experience that the term is not precisely enough specified, or can just add more questions or statements. Semantics of Business Vocabulary and Rules (SBVR) is a method that uses the "Term", "Fact type", and "Rule" as operators to express joint understanding. The term "Height tool" from the TEK10 code is used as a practical case and identifies different types of "fire truck" by using specific questions which contribute to joint understanding. Terms are not explained by the use of "official" definitions, but expressed by a limited number of questions, which can be further extended to give more balanced clarifications. The essential aspect is that SBVR is a dynamic method that can be continuously expanded. This method leads to "linked data".

*- Shared vocabulary - relation between terms – linked data*

Understanding of terms can also be supported by determining whether terms are related – or linked – to each other. Mapping these relationships by using questions or statements can be regarded as establishing links between elements of information – or as "linked data".

*- Taxonomy for re-structuring of hazard classes in TEK10 code*

Correct understanding of the fire technical term “hazard class” is essential for understanding Norwegian building codes . The guidelines of the TEK10 code present a number of examples of building types, but no clear definition. Examples of buildings in hazard class 1 are: aircraft hangar, boathouse, car port, cold storage, garage and parking garage with single floor, sawmill, shed, timber workmen's hut. Similar lists are presented for all other hazard classes. This can influence the tactical naming of a building so as to influence its placement in a hazard class – and thus also its fire protection requirements – which has an impact on cost.

The hazard class in the TEK10 code presents a taxonomy based on asking four yes/no questions. (The list of building types is in the guidance.) Depending on the answers, the use of the building (not the building itself) is classified into six different hazard classes. Graphical illustrations of the outcome of the four questions are presented as a decision tree in Figure 8. The hazard classes are not organised in an increasing order. Hazard class 2 has a dual representation and indicates that this is not a relevant criterion (question) for classification.

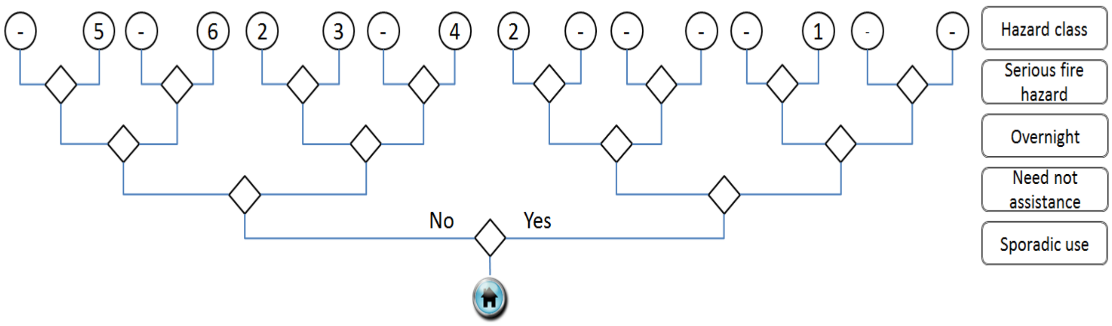


**Figure 8. Graphical representation of original TEK10 questions for identifying hazard class**

The original structure of the questions identifies all 6 hazard classes, but it can be hard to understand the use of the numerical identification without a clear hierarchy. The code and guidelines also refer to series of numbers, like hazard classes above 4, or this regulation includes all buildings in hazard classes 4, 5 and 6. Table 5 presents a way to re-formulate the question to give a more logical presentation.

**Table 5. Re-structuring of questions used in the V-TEK10 guideline**

| Do the user(s) of the building: | | | | |
|---|---|---|---|---|
| Original version | have permanent use | need assistance | stay overnight | serious fire hazard |
| Re-formulated version | have sporadic use | need no assistance | stay overnight | serious fire hazard |

Figure 9 illustrates the situation after re-organising the questions to optimise them for the simplest path in decision making. Two questions are reversed to get an increased numbering of the hazard classes. Based on making a decision, this is not necessary. However, it illustrates the logic behind the increased numbering of hazard classes. Hazard class 2 is a “separate branch” and can be re-numbered to get an increased numbering. After this re-organisation, no questions lead to “empty classes”.

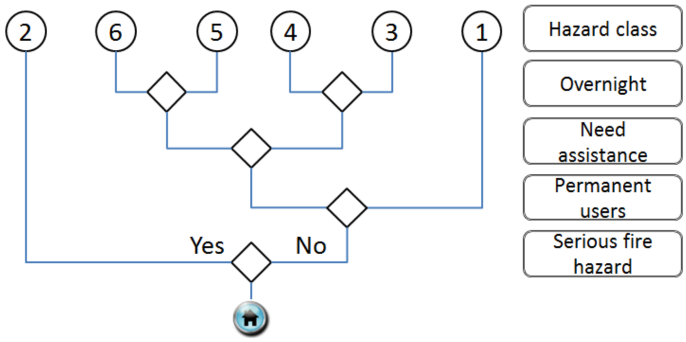


**Figure 9. Graphical representation of re-structured TEK10 questions for identifying hazard class**

This can also be regarded as a methodology for re-structuring regulations to improve and simplify their user-friendliness. As Figure 9 illustrates, only one question is needed to determine hazard class 2 and two questions are needed to determine hazard class 1 and 2 from all others.

Compared with the guidelines which present a long list of types of building, this ontology-based approach can easily identify hazard classes based on a limited number of questions. The questions can be asked by the BMC or the digital application system.

***Contribution to further studies***

This study has explored methods and software that can contribute to demystifying the use of ontology-based methods and tools for interpreting text. The challenge has been to explore the practical use of methods and tools that are simple enough to be used by practitioners in the AEC industry. This study indicates that the following methods can support this aim for increased understanding and consistent interpretation:

Terminology
- Use of Semantics of Business Vocabulary and Business Rules (SBVR)
- Development of definitions in a dynamic way

Shared vocabulary
- Linked data by use of Resource Description Framework (RDF)
- Searchable information

Restructuring of information
- Identification of relevant information
- Use of decision tables
- Foundation for BIM-based model checking (BMC)
- Principles for an increase of semantics by use of 5-star data model

The unclear and inconsistent use of terms and relations between terms has been identified, and examples for restructuring have been presented. The ontological approaches in this study have resulted in an alternative way of structuring regulations to prepare for the implementation of digital model checking solutions.

The Norwegian Building Authority has been a partner during this study. This has resulted in the development of net-based applications for guidance on whether one needs to apply or not for building permit. This indicates that the development of small practical solutions for explaining the principles of ontological engineering is useful for gaining an increased interest in ontology. The use of the explored methods has the potential to be part of the practitioner’s toolbox for interpreting text in a consistent way.

# 5 Contributions

## 5.1 BMC – BIM-based model checking

This chapter brings together the findings of the research and provides an overview of the key implications for transforming regulations into computable rules in BIM-based model checking systems. The intentions of the research have been to contribute to increased digitalisation of regulations. Exploring real regulations with an ontology-based approach resulted in three applicable methods: RASE, TIO and Tx3. These methods are presented separately later in this chapter.

Figure 10 illustrates the development of BMC as a process which combines methods in relation to the complexity of the regulation or the importance of having a computable rule. This can be done flexibly and adjusted to the constraints for the rule development project. The intention of this process is to adapt the effort in the development in relation to the complexity of the regulation or the importance of having a computable rule. One of the contributions of the research is therefore that the conversion of regulations should be regarded as a structured production process, and not as an unpredictable development process.

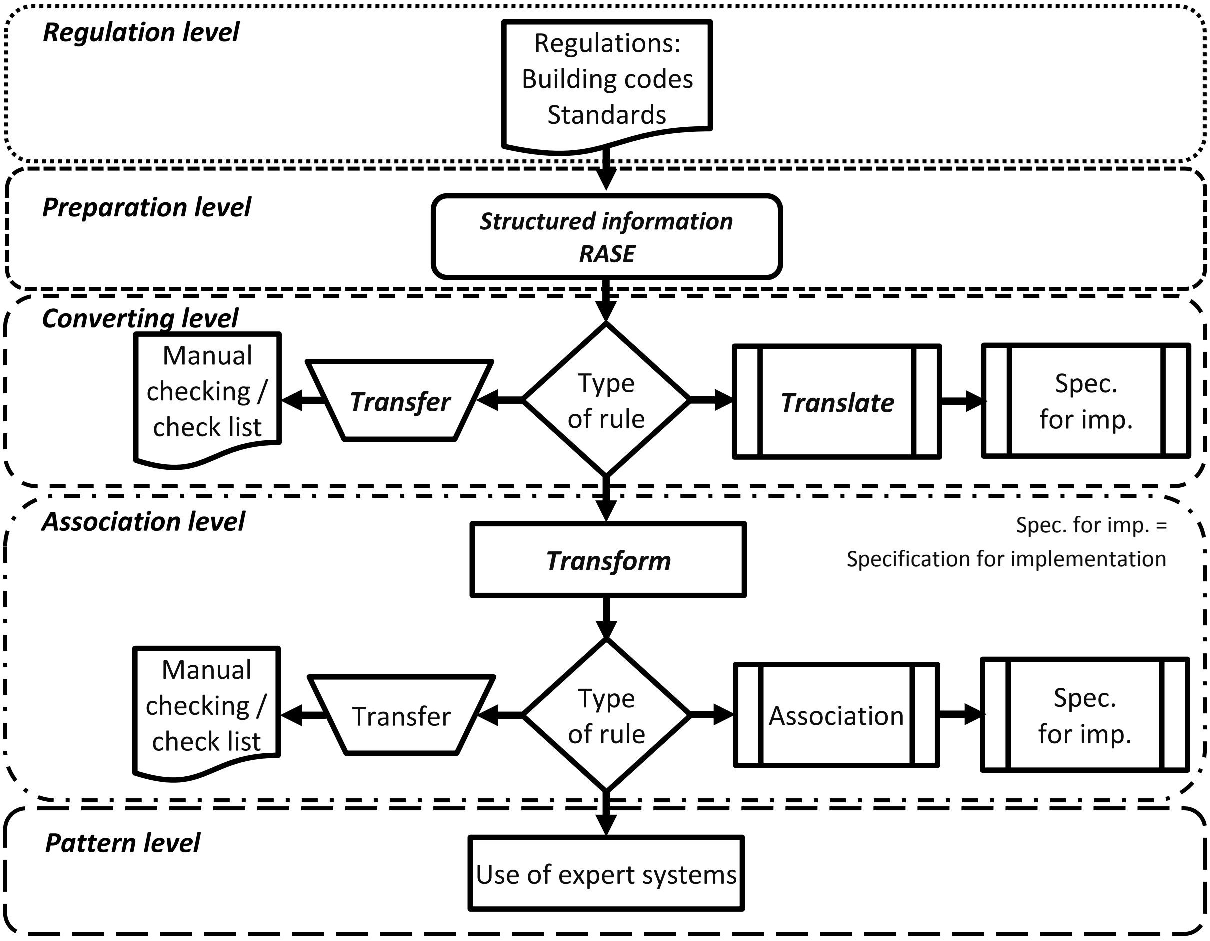


Figure 10. The BMC process - Flowchart based on Tx3 methodology

Optimisation and support from other methods, like the terminology database, is not included in the scope of this PhD-based research, and should be based on practical experience. The BMC process focuses on the use of the simplest possible methods and procedures, in addition to determining the degree of digitalisation of regulations in the front end of the project. This can contribute to an improved cost/benefit balance in rule development projects – and thereby to increased development of computable rules.

## 5.2 RASE – Requirement, Applies, Selection and Exceptions

RASE is a semantic-based mark-up methodology for identifying elements in unstructured text in regulations and transforming them into a structured form prepared for implementing into BIM-based model checking software. RASE is an abbreviation for; Requirement (R), Applies (A), Selection (S) and Exception (E). The use of mark-up colour is illustrated in Figure 11.

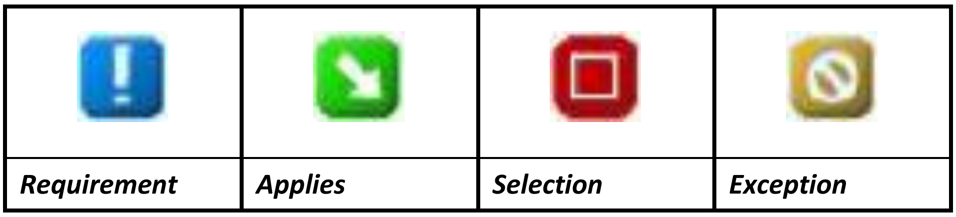


**Figure 11. The four RASE operators for rule development (Hjelseth and Nisbet, 2010)**

The use of RASE is illustrated in Figure 12, taking the example of Clause 10 "Building entrances and final fire exits" in the ISO 21542 standard. A sample of text from this standard is shown below and selected parts are marked according to the RASE mark-up methodology.

*10.5 Doorway width*

*The minimum unobstructed width of an entrance doorway shall be not less than 800 mm; 850 mm or more is recommended as more space can be required for a person using a powered wheelchair.*

*NOTE: Many national building regulations require a minimum width of 900 mm for an entrance door.*

**Figure 12. Mark-up of text in the ISO 21542 standard by the four RASE operators**

Table 6 is the tabular version of the marked up text in Figure 12. Each text element is supported by metadata which describe its attributes and values. This table presents the regulation as an applicable rule. This form of knowledge representation is a preparation for implementation in an application. The separation of "Property" and "Comparison" enables parametric analysis.

**Table 6. Clause in ISO 21542 structured into a computable rule by RASE methodology**

| Mark-up of metric phrases | Operator | Object type ¤ ) | IFC schema (or other data schema) | Property | Comp-arison | Metric *) | Unit |
|---|---|---|---|---|---|---|---|
| entrance doorway | A | DoorSet (Pre-def.) | ifcDoor Pset_Door Common | IsExternal | Equals | True | True/ False |
| unobstructed width | S | Door and frame | Pset_Door Common | Handicap Accessible ¤) | Includes | Width | |
| shall be not less than 800 mm | R | | | | ≥ | 800 | mm |
| national building regulations #) | E | | ------ | National regulations | Priority to national | Name of regu-lation | |
| unobstructed width | S | | Pset_Door Common | Handicap Accessible ¤) | Includes | Width | |
| shall be not less than 900 mm | R | | | | ≥ | 900 | mm |

**) Parametric analysis is enabled by transparent update of metric. Different levels, not only minimum, can easily be tested. The metric is stated in a positive way. True if entrance doorway is identified, and width is equal to, or more than 800 mm.*
*#) Nation is not specified, but the standard says that if national regulations are defined, these shall be used.*
*¤) Object type: Pre-def indicates that the properties can be pre-defined in the used object. The other type is "User-defined" like area for ifcZone that is defined by user of area functions in the design software.*

Property refers to an attribute in the property set (Pset). 'Handicap accessible' for people with impaired mobility will indicate that this property width is precisely defined as the unobstructed door width measured with the door at a 90° opening.

Use of the RASE methodology can serve two purposes: specification of rules for programming as digital rule sets in BMC software, and use of RASE as a requirement database. This effect can be achieved as a spin-off in developing computable rules. This implies that even if the rules, or all rules, not become implemented into BMC, starting the digitalisation process will give positive feed-back. Information structured by the RASE methodology can serve as a requirement database. RASE gives information about which requirements apply in which situation. By use of harmonized terminology, or synonym lists, requirements from multiple sources can be mapped and extend the use of the requirement database. Regulations can be structured in various ways, like topics such as Fire safety, energy, layout, accessibility, indoor climate etc. or it can be structured after different types of buildings. All those topics can include identical requirements. RASE enables a dynamic way of restructuring these requirements. Development of software combining registration (classification) and reporting (sorting/filtering) will of course support practical use.

Development of requirement databases will offer a searchable overview of all requirements related to defined situations. The situations can be new constructions or existing buildings, function in buildings (escape routes or cookery), building parts /-solutions (windows / ventilation), or users (general public or employees), type (dwelling houses or office buildings) of buildings, or size (area or height) of buildings.

Presenting proof of concept for the applicability of the RASE methodology has been done by testing the method on real regulations, and by theoretical deductions. Research by Kasim et al. (2013) about automated sustainability compliance checking process can be used to indicate proof of concept for use of the RASE methodology. This can be illustrated from the following quote from the abstract:

> *"… the RASE methodology is utilised to extract requirements from sustainability based regulations, with the goal of converting them into compiled coded rules for execution by a rule engine."* (Kasim et al., 2013).

Arguments for use of the RASE methodology is further presented in the conclusion part (ibid.):

> *"The rule based compliance checking approach relies on converting standards and best practices into complied coded rules by using a modification of the RASE methodology. This methodology allows the rules to be generated rapidly and extracts the need for manipulation of the compiled rules themselves. This is a critical issue that allows the rules to be in a form understandable by construction domain specialists without needing to understand the industry data file formats or even how the underlying rule engine will work."* (Kasim et al., 2013).

The RASE methodology supports the principle of legality. This principle is of most importance in the legal domain. It states that every rule must have a link to a defined warrant or legal basis. This enables a complete overview of which rules apply in a defined period. This feature is very useful for checking according to old regulations, e.g. when the project was first initiated – and compares this with rules in the current regulations.

## 5.3 Tx3 - Transcribe, Transform, Transfer

Tx3 – Transcribe, Transform and Transfer, is a methodology for classifying rules to express the degree of computable rules in a regulation and is illustrated in Figure 13. Transforming statements in the regulation into computable rules is regarded as an insecure process in terms of complexity, user time and expected outcome. To reduce the insecurity of these projects the Tx3 methodology can be applied.

Tx3 classifies rules based on regulatory statements, or normative text in general, into three main categories:
- Transcribe: for statements in regulations which can be directly transcribed (or transformed) into computable rules. This will often be the situation with prescriptive regulations.
- Transform: for statements in regulations which can be transformed (rewritten or restructured) in a way where the scope is maintained. This will often be the situation with function-based regulations. It will often be necessary to include constraints for use of these categories of rules.
- Transfer: for statements in regulations which cannot be implemented into BIM-based model checking software. This will be the situation when the requirements are very imprecisely expressed, with no connection between goals in the regulation and identified indicators. Instead of trying to implement these types of statement into BIM-based model checking software, it is better to identify these situations in advance.

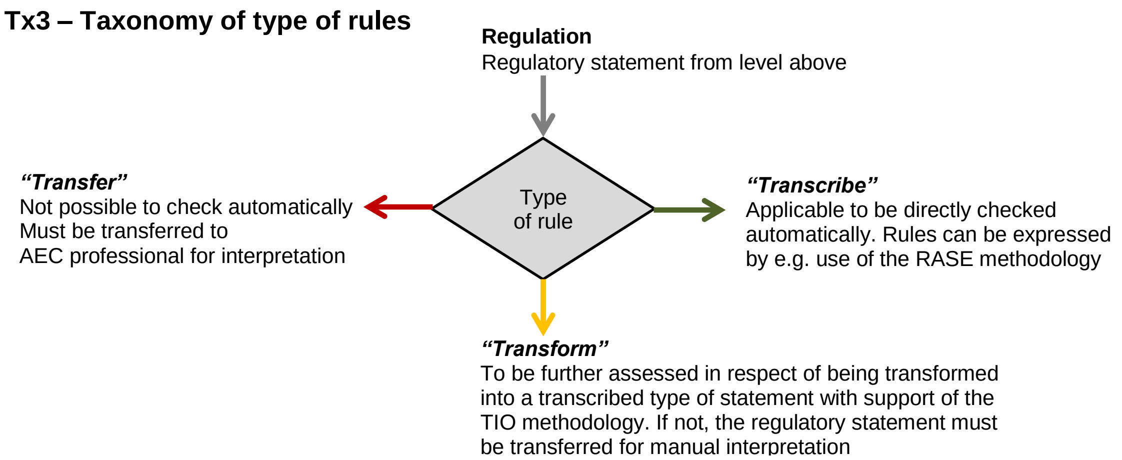


**Figure 13. Taxonomy of type of rules**

Regulatory statements classified as "Transcribe" can be expressed as computable rules by pre-defined procedures such as RASE. The challenging part is the statements classified as "Transform". Whether these statements can be expressed as (transformed to) computable rules is decided at the "Association level". "Transfer" to skilled AEC professionals for interpretation will often be the best solution for regulatory statements that are very dependent on context, with a large number of constraints and much information in the model. The process of classification can be split into more levels. A flow chart of the Tx3-methodology for transforming of regulations into computable rules is illustrated in figure 10.

The RASE methodology has the role of a "Preparation level" between the text in the regulations and the programming in the model checking software. This level is the "Transforming level". Regulations which are still classified as "Transfer" can be further explored at the "Association level". For advanced solutions, aiming to solve the last percentage of professional interpretations, statements are explored at the "Pattern level/Expert system" which looks into the use of an expert system. This classification process is also presented in Paper 5, "Experiences on converting interpretative regulations into computable rules", which is included in Annex A.

## 5.4 TIO - Test Indicator Objectives

TIO stands for Test Indicator Objectives and is an ontology-based methodology for bridging the gap between qualitative and quantitative expressions. This enables an increased degree of digitalisation by interpreting qualitative requirements in the regulations into quantitative values in the rules.

Interpreting the text in function-based regulations is essential to enable processing in BIM-based model checking software. To support this process, the TIO methodology has been developed to bridge the gap between qualitative and quantitative expressions in regulations, or normative text. The principle for closing the gap is illustrated in Figure 14.

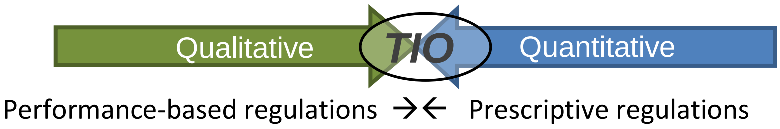


**Figure 14. Scope of TIO (modified version of Hjelseth, 2012 a,b)**

The impact is that performance-based regulations should not be regarded as a barrier to implementations for computable rules. The pressure to change regulations into a prescriptive form can therefore be reduced.

Example of TIO's based on ISO 21542:2011 standard is presented in Table 7. For enabling automatic model checking must function based requirements with qualitative metrics be transferred into quantitative metric with discrete values. This transformation will have a significant impact on the efficiency. It is important to be aware of that when the logical rule is established, then can the metric values can be regarded as parametric instances. This approach can enable performance checking at different levels; one rule-set with the minimum requirements, and another with higher requirements. Table 7 present a TIO-dictionary where qualitative goals are transformed into qualitative metrics.

**Table 7. TIO-dictionary for transformed qualitative goals into qualitative metric**

| **Clause** | **Shall/ Should** | **Qualitative expression of goal** ***text of statement in ISO standard*** | **Test Indicator Objectives (TIO)** | **Quantitative metric =, <, >** |
|---|---|---|---|---|
| ***Minimum dimension*** | | | | |
| 7.6 | Shall | ..powered wheelchair.. *If larger powered wheelchairs and scooters for outdoor use are to be considered, the outer radius of a turning space should be larger.* | Dimension of powered wheel-char, different types, in mm | *x* mm |
| 26.3 | Should | ..visually contrast... *Fixtures and fittings in sanitary facilities should visually contrast with the items and surface on which they are positioned* | Use of LRV | *x* LVR |
| 40.8 | Should | ..well illuminated... *Signs should be well illuminated with no glare* | Minimum illumination in lux | *x* lux |

Table is to be continued on next page.

Continued: Table 7: TIO-dictionary for transformed qualitative goals into qualitative metric

| Clause | Shall/ Should | Qualitative expression of goal *text of statement in ISO standard* | Test Indicator Objectives (TIO) | Quantitative metric =, <, > |
|---|---|---|---|---|
| | | | | |
| ***Maximum dimension*** | | | | |
| 6.8.3 | Should | ..as close as possible... *Location of accessible parking spaces (indoor parking) should be as close as possible to the entrances/lifts.* | Maximum distance in mm | *x* mm |
| 18.1.9 | Shall | sufficient time… *A powered swing door shall be fitted with a return delay mechanism that allows sufficient time for safe passage and for detecting the presence of a person lying on the floor within the door closing area.* | Maximum time in seconds | *x* sec. |
| ***Pre-accept solution*** | | | | |
| 18.3.2 | Should | ..easy to use; open and close.. *Windows should be easy to open and close. It should be possible to open and close the windows with only one hand.* | Pre-accepted (approved) type of window | Approved by *x* organization |
| 26.5 | Shall | ..easy to open and close.. *The door shall have an unobstructed width of at least 800 mm, with minimum 850 mm as a recommended value, and it shall be easy to open and close. The door should open outwards.* | Pre-accepted (approved) type of window | Approved by *x* organization |
| ***Product property – Surface*** | | | | |
| 6.7 | Shall | Kerbs...slip-resistance.. *Kerbs shall have a slip-resistance surface.* | Specify friction coefficient on kerbs | 0.*x* |
| 25. | Shall | Walking surfaces…slip-resistant.. *Walking surfaces shall be slip resistant.* | Specify friction coefficient for walking on terraces, verandas and balconies | 0.*x* |
| 26.3 | Shall | Floor surface…shall be slip resistant.. *The floor surface shall be slip resistant, anti-glare and firm.* | Specify friction coefficient for floors | 0.*x* |
| 31 | Shall | Floor coverings…slip-resistant in both dry and wet conditions.. *Floor coverings shall be firm and slip-resistant in both dry and wet conditions.* | Specify friction coefficient for floor coverings | 0.*x* |

# 6 Discussion

Chapter 5, Contributions, presented an overview of three methods and the concept of BIM-based model checking about *how the research results can contribute* to specification for the development of applicable rules. This discussion chapter now includes reflections on *how the research questions are answered and limitation in the study*.

The research was conducted between 2009 and 2015. During this period the researcher, the research community, the BIM community, AEC industry and society have all undergone development and change regarding the use of BIM and digital services.

Despite the increased focus on BIM itself, this research cannot see the same development in BIM-based model checking of regulations. This situation is addressed in Paper 6 on BIM-based model checking. One observed reason for this situation is that this problem is complex and not easy to solve. Especially the focus on BIM-based model checking in the public sector has increased in significance during the research period. There are now established public programs for development of the public sector and the AEC industry. The UK and Norway have initiated projects with a clear focus on automatic processing of building permit applications (Refvik, 2013). However, it is not yet possible to find any implemented digital solution for the checking of building permit applications, or other types of BIM-based model checking. This can be regarded as reflecting that it remains a challenge to convert regulations into computable rules.

The limited research in this PhD study does not provide a complete answer to how to solve the complex set of problems involved in the development of BIM-based model checking systems. It contributes methods that are connected with the AEC industry regarding limited investment and time to develop BMC solutions. The proposed methods can and must be supplemented with other methods to ensure a complete process. The process of transforming regulations will be eased if the regulations have a well-documented and structured terminology. The development of a uniform terminology is not directly included in the research, beyond its relation to ontology.

Continuous awareness of validity and reliability is essential for the selection of research methods for solving the research problem, including the three research sub-questions. Validity can simply be regarded as solving the "right thing", while reliability is about doing the "thing right" (Samset, 2007). This thesis is based on a multi-disciplinary approach which also includes the industry perspective. Validity (or relevance) is domain-specific. The legal domain focuses on "digital-friendly regulations", and case-based interpretation (Schartum, 2012). Change of regulations is a time-consuming process which is also influenced by political decisions about the regulations. The focus is therefore turned to the interpretation of existing regulations.

The construction domain has its focus on identifying practical solutions and situations. The large number of regulations is in itself a problem and it is in practice not possible to check compliance manually. The support of BMC, even for parts of a regulation, will therefore be useful. This can reduce the stress involved in solving the hard problems before programming into BMS can be started. Within informatics, the advanced models and semantic technology used are regarded as enablers. Social and cultural aspects of the use of BMC solutions are not within the scope of this research. The business models in the AEC industry, on the other hand, do not provide economic constraints for the use of advanced semantic methods. The awareness of the domain-specific challenges has directly and indirectly influenced this research in terms of its extent and direction. The variation between all aspects has been a challenge throughout the research - and this made it important to go into greater depth on each aspect: theories, literature studies, methods, practice, development of software to verify specified rules, and specification of future regulations.

There is a balance between the development of applicable methods based on theories and analysis of theories for interpretation of text in regulations into computable rules; in this research the choice as been to focus on methods as the outcome.

The scientific work is based on the development of a theoretical foundation for the proposed methods, based on literature studies and cases from real regulations. This approach is chosen due to priority of development of applicable methods based in combinations of theories. Arguments for choose of theories could in this respect have been more extensively analysed. An example of this may therefore be that the RASE methodology should be discussed more in relation to natural language processing (NLP), and that the introduction of controlled natural language processing (CNL) should be explored in depth. Use of CNL is regarded as a specialisation of NLP, and the theoretical pros and cons could have been given more attention to give the methods a more directly connection to one theory, or the most dominating theory.

The multi-disciplinary approach includes disciplines from the legal, informatics and construction domains. Much research has been done in these three domains which have been very important to establish the theoretical foundation for the developed methods. The multi-disciplinary approach is a contribution to seek a solution in one domain that is still considered a problem in another domain. One effect of this approach is that this research has not gone deeply into each domain and tried to solve the hard problems with each domain. An example of one of these challenges within construction is how to get relevant information in the BIM file. Within informatics is one of these challenges consistent use of terms in all rules and automatic process of transforming specification into applicable software code. Within legal sciences is one of these challenges to have universal valid interpretation of regulations, and to accept that the rules can be processed on the basis of a limited and predefined set of information.

The studies have to a limited extent discussed theories comparatively against each other. This can be a subject for further research on theories for BIM-based model checking. The interpretation of text can be claimed to be a question of logic. In this respect, advanced use of “first order logic” (FOL), for example, can contribute to an overview of regulations, and the use of semantic-based theories in this respect is a solution based on limited understanding of FOL. Another aspect of focusing on theory may be to discuss the use of fuzzy logic versus FOL, by introducing the fact that there are a limited number of design solutions that can be checked- and the use of ”compliance” with a delimited number of pre-accepted solutions (pre-accepted solutions are often specified by certification organisations, like Sintef-Byggforsk in Norway).The use of fuzzy logic can be claimed to reduce complexity, and to simulate the way practical compliance checking is done in real projects. On the other hand, these examples illustrate that BMC solutions can be based on a theoretical foundation, and not only on best practice and the utilisation of the functionality in existing software.

During the working period of this study, implementations into software have been suggested as a way to “prove” that the proposed methods work in practice. The development of software solutions is proposed as one of the options for further development. Use of the RASE methodology has been supported by the Require1 software developed by Nick Nisbet. The use of this software is currently at the prototype stage, which makes the mark-up process more visual and dynamic. It replaces moving the text into tables. From a research point of view, an application will only influence the production capacity, not whether the theoretical semantic issues can be solved. The Norwegian Building Authority has funded a project with 50.000 Euro (DIBK-RASE, 2014) to develop a software tool based on the RASE methodology. This can be regarded as an indication that reliability and relevance are given priority in this research. Software implementation does not directly address validity, but applicable software implementation indicates that this support can solve the research problem with software tools to be used by professionals in the AEC industry.

Regarding validation of developed methods is testing of outcome a simple way to verify if the result in correct result. All methods have been tested on real regulations. However, testing the end result in a process is more time and cost consuming than testing the input to a process. A stepwise process recommended where outcome can be assessed by legal and construction expert can be a way to extend testing beyond cases used in this study.

This study have basis in existing theories, and uses combination for these extant theories as foundation for development of methods. This indicates need for dedicated theories relating to transforming are a missing link. This study contribute with methods, put have potential to be used as a foundation for further studies in development of theories for transforming normative , and domain specific, texts into computable rules. This type of theory could also be supporting legal theories for digitalisation of regulations.

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# 7 Conclusion

## 7.1 Answering the research questions

This chapter presents the answers to the research questions introduced in the first chapter.

The research question is divided into three sub-questions:

Sub-question 1: How can building regulations be structured to support BMC?
Sub-question 2: How can structured regulations be interpreted to support BMC?
Sub-question 3: How can BMC be developed, maintained and scaled?

These together intend to support the overall research question:

How can regulations be converted into computable rules in BIM-based model checking systems?

The following sub-chapters present each of the three sub-questions and the research question. The final sub-chapter presents proposals for further research

## 7.2 Answering SQ1: How can building regulations be structured to support BMC?

***How is this question answered?***

The overall answer to this research question is that it is important for text in regulations to be presented in a structured and transparent way. This question is answered in papers 2, 4 and 5, which focus on reduction of complexity and enabling an overview of the scope of each rule in a regulation. Without a very clear understanding of what the regulation is about, transforming it into computable rules is untrustworthy. The use of ontology is essential, but it has been hard to see this being included in the development and formulation of regulations. The legal tradition of being case-based means that interpretation of the regulations requires unique information or facts with reference to each individual case. This does not align with a system approach and the use of explicit specifications. Defining what information is required in the BIM file to process a rule can therefore in itself be a challenge. Understanding the terms used in the regulations is an obvious challenge. Standards have their own traditions for including terms and definitions. One approach could therefore have been to look at the decomposition of each element. If all terms are defined precisely, then it should be possible to build systems. However, this micro-perspective can easily lose sight of the intention and fail to be applicable. Every problem will be answered with more systems for ever smaller parts.

However, good definitions and consensus on the interpretation of terms are essential. Terminology is identified as a significant part of transforming regulations into computable rules by means of establishing a joint vocabulary. This study has tried to take an integrated approach, focusing on the connections between regulations by identifying the scope of each regulatory statement. The regulations must be restructured from text in sentences to text in a structured and machine-readable/ machine interpretable format. The theoretical approach to this sub-question has been answered by focusing on ontology engineering and knowledge representations. Structuring of regulations into tables which identify scope, metric value, logic and reference to regulation can be regarded as "rule engineering" with theory based on ontology engineering and knowledge representations.

***Proposed methods***
Even if the research is not about the development of software applications, awareness of applicable methods for programming and implementation has been a guideline. The scientific foundation has been based on ontology engineering and the principles in the methods must be applicable without the use of software. However, the right software would increase the capacity to structure regulations and prepare for programming.

The RASE methodology proposes a solution for the classification of normative text, like text in regulations, through the use of four operators: Requirement, Applicability, Selection and Exceptions. This classification is done by an AEC professional who is familiar with the terms used in the regulation. This results in table-based knowledge representations which give the professional reader a precise overview of where each rule in the regulations applies.

The methodology is intended to be used in an application. Part of the study used a prototype developed by Nick Nisbet in AEC3. However, this could also be done manually in a table in a word processor. Use in an application enables functions to add more information to each text element. The Norwegian Building Authority (DIBK-RASE, 2014) has started the development of an application based on the RASE methodology. This application can improve capacity and prepare for machine-interpretable regulations.

## 7.3 Answering SQ2: How can structured regulations be interpreted to support BMC?

***How is this question answered?***
An applicable way of interpreting regulations will be a significant support for implementation into BIM-based model checking. Answering this question is included in all papers, but is especially in focus in papers 1, 2 and 7. The research has an applied approach for the AEC industry which implies the search for specialised solutions, which should be as simple as possible. Reduction of complexity has therefore been a guideline when answering this research question. The scientific approach therefore focuses on identifying a relevant theoretical basis for a domain-specific solution. Tarski (1935) stated that applied solutions can only be realised within limited domains because the complexities in the real world are too extensive. The concept of “knowledge soup” was presented by Sowa (2006), who follows up this approach by focusing on the complexity in the word itself – and not the words – that make things complicated.

The approach to the interpretation of text is therefore delimited to normative text, which is the type of text used in regulations (and similar types of documents for requirements and specifications, e.g. contracts). The first step in the interpretation of text in regulations should be done by an AEC professional. This implies that Natural Language Processing (NLP) and other general semantic-based methods take too broad an approach and are therefore not applicable. So the use of Controlled Natural Languages (CNL) is more relevant. Interpretations of terms can focus on identifying delimiting criteria, which is much simpler than the specification of definitions. The Semantics of Business Vocabulary and Business Rules (SBVR, 2014) is an example of this type of methodology.

A very relevant problem is how to interpret performance-based regulations. Prescriptive-based regulations are in a way prepared for implementations. Ontology focuses on “what a thing is” and in this respect is a very useful approach for the interpretation of regulations. Looking at what the regulation is intended to regulate can provide a guideline for interpretation of the regulations into rules. Use of the rules can be delimited by introducing constraints, in order to enable trustworthy interpretations within a defined scope.

***Proposed methods***
There are more methods that can be regarded as supporting this research question. The Tx3 methodology enables determination in advance of starting to convert the regulation. It can be used to assign priorities among regulations to those requiring the highest degree of computation. The TIO methodology contributes with an approach for reformulation of the requirements used into computable rules. Both these methods support the use of the RASE methodology.

## 7.4 Answering SQ3: How can BMC be developed, updated and scaled?

***How is this question answered?***
Sustainable development implies that all phases are taken into account in the development of computable rules. This implies that it is not enough just to implement the easy regulations as fast as possible, but to include time, cost and quality with all phases in the life-cycle of the rule.

This question is focused on in papers 3, 5 and 6. Paper 3 focuses on roles and responsibility for relevant input of information in the BIM file. Relevant input is critical for the processing of the rules in BMC. Paper 5 focuses on different levels of effort in transforming regulations into computable rules. The case study on a complete standard confirms that the applicability of regulations can be determined in advance of programming. Even if it possible to convert regulations by the use of more advanced methods, this can in the next phase have negative repercussions for the maintenance and scaling of the BMC solution. By being aware of these regulations in advance, the development project can be designed in ways that produce more rules for less effort. Paper 6 on BIM-based model checking (BMC) is highly relevant for including the applied perspective.

This question can also be regarded as one to establish methods that are acceptable within the conditions in the AEC industry. This stresses time- and cost-effective development by using the simplest methods possible. The use of the BIM as the container of information about the project to be checked is taken as a postulation for the development of solutions. In addition to saving the time and cost of re-entering information into a model checking system, the use of BIM enables the specification of the information that is relevant for model checking. This research has focused on the identification and specification of relevant information as one of the core elements in both development and practical checking of computable rules.

***Proposed methods***
This sub-question is covered by a combination of the RASE, TIO and Tx3 into a BMC processes. This can be done flexibly and adjusted to the particular constraints of the rule development project.

- The Tx3 methods can be used as a framework for answering this sub-question. This method contributes to determining the degree of digitalisation of regulations. This enables the use of relevant methods for further development. The reduction of complexity contributes to the use of the simplest methods and procedure possible, and thus influences the updating and scaling of the rules.

- The TIO method enables an increased degree of digitalisation by interpretations of qualitative requirements in the regulations into quantitative values in the rules. The support of set based constraints contributes to enable validity for practical use.

- The RASE methodology can be processed manually. It provides a low cost methodology for transforming existing regulations into a structure that can be used as a foundation for the development of computable rules. It should therefore be possible to realise the cost/benefit and flexibility in the use of RASE – and in this way to contribute to the continuous and sustainable development of BIM-based model checking systems.

## 7.5 Answering RQ: How can regulations be converted into computable rules in BIM-based model checking systems?

The answers to all the research sub-questions are intended to support the answer to the main research question. The three sub-questions are answered with reference to methods. The methods are founded on scientific theories and established methods. The developed methods can be combined as a process based on combinations of different methodologies. The selection of methods supports the process of developing computable rules applicable for BMC.

The research results give practical examples on how regulations can be converted into computable rules in model checking systems in a predictable way. These experiences imply that one can start transforming regulations into computable rules in BIM-based model software by using relatively simple methods. This in turn implies that it should be possible to start up rather small projects.

Optimisation of the methods and process was outside the scope of the research. The Discussion chapter referred to the limitations of the research outcome. However, it is expected that practical experience, support from supplementary methods and the development of software based on the RASE, TIO and Tx3 methodology will have a positive influence on development of BMC. The large number of regulations in the AEC industry, increased use of BIM in general, and the limited implementation of regulations in BMC indicate that even if the proposed methods are not optimal, they can have a positive effect on how building regulations are implemented in BMC.

It is important to keep the needs of the AEC industry and its users in focus. Using the idea in Henrik Ibsen's "The Pretenders" (1863) of the "master concept" ("Kongstanke" in Norwegian) for future digitalisation of regulations, the master concept must be to ensure that the solution for digitalisation of regulations reflects the users' needs. A high degree of context awareness and the use of self-service solutions can expect to be included in the projects. This master concept is highlighted in Figure 15. However, this is highly ambitious. Hopefully, some of the outcome from the research can be used to reduce the gap between today's situation and future opportunities.

*Master concept for future digital solutions:*

*Develop digital solutions that ensure the regulations reflect the users' needs*

**Figure 15. Master concept for future BMC**

## 7.6 Implications for further research

***General***

This study has focused on systematisation, the first phase in the development of computable rules. Following the chain of information into subsequent phases will therefore be relevant topics for further work. Further research can go in different directions. The outlines below illustrate some of these directions.

***Experience from practical use***

Following real projects which develop computable rules will be a very good resource for optimisation and to identify missing methods or tools. The methods from this research do not, of course, cover all the methods or tools for an optimal development process.

***Development of software support***

Practical development of computable rules, and especially in large-scale development, needs to be supported by relevant software tools. It is important to be aware that regulations change, and updates have to be on time and cost-efficient – and without unintended consequences for other rules. It is especially the RASE methodology that will benefit from support from a software tool.
Software tools can be developed in more directions:

- Support for programming – rules prepared for machine interpretation. Some kind of pseudo-code can be an inter-stage solution. The outcome from this type of software tool will be specification for programming.
- Specification of required information – processing of rules requires relevant information.
- Requirements database – will offer a searchable overview of all requirements related to defined situations. This function can be solved by sorting functions for sorting, filtering and grouping of registered rules.
- Testing of regulations – this can include both existing and new regulations. The RASE methodology has to be supported by good functions for reporting and presentation of the scope and requirement of each regulation. The primary outcome of this will be proposals for revisions to regulations, and not computable rules.

The Norwegian Building Authority has started a project for the development of an application based on the RASE methodology (DIBK-RASE, 2014). Adaptation of templates in software support based on semantic technology can also be relevant to support the specification, development and testing of computable rules.

***Process for digitalisation of regulations***

The development of knowledge systems in general and model checking systems in particular should be regarded as a multi-disciplinary project. It is also important to be able to learn from other disciplines. BIM-based systems are easy to regard as AEC-specific systems, but product and process modelling are common to all industries. The informatics of the law is a closely related domain and can be a relevant research community for further collaboration. The use of the proposed methods like RASE, TIO and Tx3 are candidates, but these need to be supported with other methods and tools or procedures. By developing a joint framework for digitalisation of regulation, one can achieve time- and cost-effective development of computable rules. Research with a focus on organisational topics is therefore a relevant domain for improving the development of computable rules.

***Support for re-design of regulations***

Future development of regulations should be adapted for digital implementation. This is what Professor Dag Wiese Schartum (2011) at the Informatics of Law faculty of the University in Oslo calls "digital friendly regulations". Use of the proposed methods from this thesis is a candidate for testing if the proposal for the regulations is applicable for implementation or not. If not, there must be an iterative process. If the regulations can be structured into *RASE tables*, this indicates a high degree of digitalisation. A multi-disciplinary approach will naturally be part of this process.

***Support for public projects for digitalisation of regulations***

There is an increased focus from national authorities (Refvik, 2013) on public projects for digitalisation of regulations. ByggNett from the Norwegian government is an example of these initiatives. As part of digitalising public government, the Norwegian Building Authority has taken the initiative to digitalise building regulations. A formal concept evaluation, "ByggNett – The collaboration platform for the AEC industry" (Norwegian) was finalised by March 2014 (DIBK-KVU 2014). Automatic processing of building permit applications is one solution with a high priority. These types of project have resources to include research.

***Specification of new rules***
It is a challenge to specify computable rules and commercial developers do not normally enable users to specify new rules. They have options for updating parameters in existing rules, but not for new rules. This will enable BMC software to be customised for project-based use. Implementation of requirements from IDMs, guidelines and contracts can be specified as computable rules and thus be checked by the architect or engineer before submission to the contractor or other users.

***Theories for BIM-based model checking***
This study has accentuated an applied approach and combination of theories. This can be a subject for further research on theories for BIM-based model checking (BMC). One perspective is to focus on different concept like first order logic (FOL) for linear logical correct approach and compare this to other types of logic as fuzzy logic. BIM-based model checking depend both on rules and input for rules. Input of information could there extend the perspective of BIM to see input – and missing input - in relation to big data approach enabled by semantic technology. The benefit can contribute increased use of BMC buy easy specification of rules and use of incomplete BIM from ongoing projects.

***Integration with buildingSMART bSDD and Regulatory Room***
Development of solutions for digital compliance checking of regulations and requirement are topics with international relevance. Even if regulations and requirements will be at national, company or project level, will interpretation of terms and solutions for exchange of information be a joint element. I this respect can use bSDD be used for mapping ontologies bSDD (2015).

The buildingSMART International "Regulatory Room" is focusing on regulators need for information and the processes related to building permit (Karlshøj, 2015). In this respect can outcome from this research can contribute to standardised method for interpreting regulations and requirements into applicable rules in BMC.

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# Annex A: Research papers selected as part of thesis

**Table 8. Overview of publications presented as part of the PhD thesis.**

| Presented as paper # | Title of paper<br>Information about publishing in journal or presentation at conference | Year |
|---|---|---|
| **Paper 1**<br>8 pages | **Overview of concepts for model checking**<br>Presented at the CIB-W078 Conference in Cairo, Egypt, 16th – 19th October 2010. Co-author: Nick Nisbet.<br>https://www.academia.edu/873824/Overview_of_concepts_for_model_checking | **2010** |
| **Paper 2**<br>11 pages | **Exploring semantic based model checking**<br>Presented at the CIB-W078 Conference in Cairo, Egypt, 16th – 19th October 2010. Co-author: Nick Nisbet.<br>https://www.academia.edu/873826/exploring_semantic_based_model_checking | **2010** |
| **Paper 3**<br>16 pages | **Exchange of Relevant Information in BIM Objects Defined by the Role- and Life-Cycle Information Model**<br>Published in Architectural Engineering and Design Management, Special Issue: "Integrated Design and Delivery Solutions", pp. 279-287(9), 29th November 2010. ISSN 1745-2007, Online ISSN: 1752-7589.<br>http://www.tandfonline.com/doi/abs/10.3763/aedm.2010.IDDS5#.VRor6PmUd8E | **2010** |
| **Paper 4**<br>10 pages | **Capturing normative constraints by use of the semantic mark-up RASE methodology**<br>Presented at the CIB-W078 Conference in Sophia-Antipolis, France, 23rd – 26th October 2011. Co-author: Nick Nisbet.<br>http://2011-cibw078-w102.cstb.fr/papers/Paper-45.pdf | **2011** |
| **Paper 5**<br>10 pages | **Experiences on converting interpretative regulations into computable rules**<br>Presented at the CIB-W078 Conference in Beirut, Lebanon, 17th – 19th October 2012. http://cib2012.org/<br>http://itc.scix.net/data/works/att/w78-2012-Paper-2.pdf | **2012** |
| **Paper 6**<br>29 pages | **BIM-based model checking (BMC)**<br>Peer-reviewed chapter in an anthology. Planned to be published winter 2015 in: "Building Information Modeling: Applications and Practices in the AEC Industry", American Society of Civil Engineers.<br>http://www.asce.org/computing-and-it/computing-and-it-books-and-standards/ | **2015** |
| **Paper 7**<br>19 pages | **Trustworthy interpretation of normative text by use of ontology**<br>Peer-reviewed chapter in an anthology. Planned to be published winter 2015 in: "Ontology in the AEC domain: A decade of research and developments", American Society of Civil Engineers.<br>http://www.asce.org/computing-and-it/computing-and-it-books-and-standards/ | **2015** |

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**Paper 1**

# Overview of concepts for model checking

Presented at the CIB-W078 Conference in Cairo, Egypt, 16th – 19th October 2010.

Co-author: Nick Nisbet.

Download at: https://www.academia.edu/873824/Overview_of_concepts_for_model_checking

Published: 2010

8 pages

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# OVERVIEW OF CONCEPTS FOR MODEL CHECKING

Eilif Hjelseth, Ph.D. student, eilif.hjelseth@umb.no
*Norwegian University of Life Sciences (UMB), Dept. of Mathematical Sciences and Technology, Norway*
Nick Nisbet, Director, nn@aec3.com
*AEC3 UK Ltd, United Kingdom*

## ABSTRACT

This paper presents an overview of concepts for model checking. This have resulted in a description of four different concepts based on the intention for checking. The four concepts are: a) Validating systems, b) Guiding systems, c) Adaptive systems and d) Content based checking. By use of an ontological approach we propose a four level taxonomy of model checking 1) Intention, 2) Result, 3) Rule set and 4) Type of products. Model checking should be regarded as a knowledge system for support of the design process.

**Keywords:** checking, ontology, BIM

## 1. INTRODUCTION

This paper develops an overview of concepts for model checking in BIM (building information models). The complexity in the design, building and facility management process is increasing. According to Ingvaldsen, (1994, 2001) can as much as 40% of the defects can be related to blunders in the design process. Model checking software has achieved increased interest and is often regarded as one of the big benefits by using BIM / IFC based software in the design process (SmartMarket Report, 2009). Model checking is normally done by use of stand-alone applications as Solibri Model Checker, SMARTcodes, ePlanCheck, AEC3 Compliance or EDM Model Server (Bell, Bjørkhaug and Hjelseth, 2009).

An often used example of model checking is clash detection to validate if for example different types of pipes intersect each other. Another example can be to check if the width of the doors is according to codes of accessibility. However, there is a common perception that model checking is about validation and yes/no answers.

The full range of model checking concepts can be regarded as a framework for utilization of existing “knowledge systems”. The use of this must support the focus on doing the right things – and doing the thing right. To do this, a number of approaches have to used. Different concepts of model checking (not only validating) can be contribution in this effort. There is reason to assume that too much validation and code compliance can be contra-productive with respect to development of new ideas and solutions of the built environment. Supplementary concepts with other intention can be introduced.

## 2. THE FRAMEWORK OF CONCEPTS FOR MODEL CHECKING

Model checking used wisely is a way to share and utilize knowledge. But model checking can easily be misused by thinking that passing a validation check proves a good design of the building. At its best, one can avoid bad design solutions. This is not a bad target itself. Model checking can be regarded as a part of a knowledge system. With an ontological foundation, is should be possible to build a scalable system with trustworthy result. The challenge is to reduce the "knowledge soup" made of; a) Over-generalizations, b) Incomplete definitions, c) Conflicting defaults and d) Unanticipated applications. (Sowa, 2006).

The AEC industry can also learn from other industries when implementing these expert systems. Experiences from the oil and gas industry, model checkers were one of the main levers for utilizing product models. The increased interest for BIM and interoperability through open standards as IFC will be a driving force enabling model checking for a large number of design software based on IFC-export / import. BIM based model checking is based on processing of information supported by a semantic system for automatic generation of applicable code. This will according to Hjelseth and Nisbet (2010) enabling a cost and time effective solution.

There are several terms in use such as rule checking, validating, code compliance checking for what we have defined as “Model checking”. Model checking is used as the general term for several reasons. The checking is performed on a “model” and the information it contains[1)]. This will often be a file in IFC or ifcXML format from design software. It also gives a reference to utilization of BIM. A look-up in the ISO Concept Database (ISO, 2010) do not contain any of the terms above. The term Model checking is well described on Wikipedia, while rule checking and code checking is not. (Wiki, 2010). This is an indication for use of model checking as the preferred term for this function. In general, ontology is the study or concern about what kinds of things exist. In information technology, ontology is the working model of entities and interactions in some particular domain of knowledge or practices, such as electronic commerce or "the activity of planning." In artificial intelligence (AI), ontology is, according to Tom Gruber, an AI specialist at Stanford University, "An ontology is an explicit specification of conceptualizations, used to help programs and humans share knowledge (Gruber, 1993). The knowledge perspective is also supported by Hendler et. al. (2000) who almost equates ontology with knowledge base. Shakeri et.al. (2001) present in Figure 1. the relations from meta-model and ontology to knowledge model.

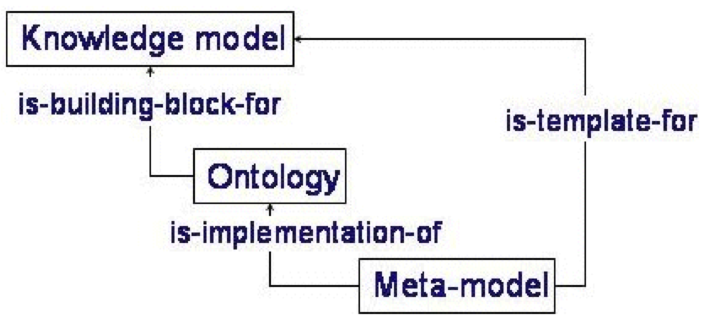


Figure 1: Knowledge model – Ontology – Meta-models (Shakeri et.al. 2001).

We propose a framework based on four different "intentions": a) Validating, b) Guiding, c) Adaptive design and d) Content based checking. The presented concepts are described by general terms that are a part of a class (classification) who is defined by taxonomy as part of an ontology. Based on this we want to present and ontology for classification model checking system. These four concepts are described in the following chapters.

[1] This makes a distinction to database and text based search systems or similar based AI (artificial intelligence) systems. The information in a model is also ordered in a pre-defined system, as with IFC where slabs and walls are related to a defined floor

## 3. VALIDATING MODEL CHECKING

The purpose with a validating checking is to determine if the content in the model is in accordance to a code, standard, regulative etc. Validating model checking is performed on predefined criteria and result in an Yes / No answer. The rule will have constraints with which set the limitations of values or existence / not existence of an object. To pass a validity test, the rules must not be activated. This indicates that missing rules or invalid constraints can make a model pass the test. For trustworthy results, the user must be aware of what is being checked and what is not. If not, it becomes too easy to pass an automatic model check which will discredit automatic model checking systems. An example is automatic accessibility checking. This cannot be checked automatically without a definition of accessibility which involves a large number of rules. However, if rules for accessibility are based on a defined standard, checking within this domain of computable rules can be done trustworthy (Hjelseth, 2009b).

***- Geometry based checking – Clash detection***

Clash detection and checking of component pairs is maybe the most 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 object (in addition to tolerance) it is possible for the designer to check and correct other distances for example between cabinets for fire extinguisher. 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 on 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 if this is a failure to be solved or just an over reporting. The checking is in practice a semi-automatic process with high degree of transparency in the checking process.

Clash detection checking has a tendency to report too many "issues". An example of this is when a pipe goes through six beams, is this one issue or six? Or if a beam goes through six pipes, is this one issue or six? Normally one will get six reports of errors in both cases, but the answer should depend on rules and the information about the pipe. In an office building, the structural beams may have priority and the expected solution is re-positioning 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. In software systems one will combine more of the concepts presented here. But without a clear understanding of what the system does (and does not), reporting of errors, suggestion to solutions, the information used in the rules and the rule itself.

***- Compliance checking / rule checking***

The purpose is to check if the solutions in the model are in accordance with codes, regulations, standards and so on. Automatic management of building permit application has long been a beacon for model checking. One reason is that permitting is a critical point that all facilities have to pass. The first large scale implementation was in Singapore in the CoreNet project for assessment of building applications. Developments at the US International Code Council may lead to another example of large scale implementation.

The rules are often clustered into rule-sets to 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 connection to KBE, knowledge based engineering and to AI, artificial intelligence (Hjelseth, 2009b). On the other hand, we are now beginning to get standards based on BIM and with AEC industry based approach in the series of IDM standards. The IDM standard,ISO 29481-1:2010, contains following components: Process maps (PM), Exchange requirement (ER), Functional Parts (FP) and Validation Rules (VR), and Business Rules (BR).

## 4. GUIDING MODEL CHECKING

The intention with this concept is to guide the designer to consider a larger range of realistic solutions than is practical without this support. It is particularly relevant in areas where the designer is not the expert or experienced. The checking is based on two elements: Identify rules for the situations where "problems occur", and second, present a list of possible actions. The rules are activated on defined situations in the model, which provides a range of possible, but relevant questions / solutions. A situation can be identified by a large number of elements. This can be visualized as a decision tree where you somewhere in the middle, getting suggestions for next branches. As an example of complete model guide:

In Norway ->
Dwelling house ->
The area is above X $m^2$ _>
A chimney and open fireplace is modeled.
Next options to be considered:

1) Add a stove for heating.
2) Increase the volume of concrete so it act as a heating reservoir.
3) supplement with a technical room for wood pellet heating in lowest floor.

There can be links from the suggestions to more information, details and calculations, experiences and examples.

This concept for model checking can also be regarded as a “learning system” or “experience utilization”. Manual version of this exists in check–list or collection of product documentation and old projects. The problem is that this is within your own domains, and often as “tacit knowledge”. The challenge is how to let other use this “experience” and to “remember” to use this (identify the problems and find solutions) in practice in an on-going project. Another aspect is that it motivated to go one step further before one turn down a solution being to expensive, complicated, not possible here – and so on. This checking can be done in all stages and all actors in the design process.

***- Pre defined solution checking***
This checking identifies a situation and suggests a predefined solution. This solution can be related to product or to work (assembly) process. This concept will normally be based on automatic lookup in the knowledge library as e.g. the Byggforsk knowledge system (BKS) from Sintef Byggforsk (2010). The list of “accepted” solutions must then be further be analyzed.

***- Search based solution checking – IFD***
This concept of checking is based on search based on concept. IFD is classification concept based on relevant products is mapped against a concept, e.g. a door. This concept, generic door, has attributes which make it possible to match this against real products. A search in the IFD library compliant product databases will list the possible products. The search can be developed as a rule and run automatic. An example is searching for a “Door” this is in IFD defined as what in UK is defined as a Door set , and in Norway as a door leaf + door-casing. The criteria is geometry: to fit into an opening in the wall that is 900 mm wide and 210 mm high, opening direction, Fire rating class, Outdoor with lock, environmental labels / ECO labels and so on. General policies as lowest price, local vendor or vendor from a predefined list can also be included (Hjelseth 2009c).

## 5. ADAPTIVE MODEL CHECKING

The intention here is to let the object itself register its environment and adapt automatically to this by following embedded pre-defined rules... The design process is dynamic and it is therefore a big challenge to update all consequences of an update. This concept of model checking will often be very useful on areas / domains where you are not the expert. There are two levels of adaptive model checking; object and system level.

***- Adaptive object / parametric objects/ intelligent objects (object level)***
An example of this concept is automatic adaptation of the diameter of column related to number of floors, and definition of Zone – Load per area. The column change diameter automatically. The adaptation can also be a concrete with compressive strength, or more reinforcement. This adaptation can be based on calculations, heuristics or preferred solutions.

Another example is based on fire rating where doors and window specifications change dependent on the fire rating of the walls in which they occur, or the spaces they bound. If you try another layout or change area, then you change fire rating values – and for consistency this changes the specification of the doors, windows and walls etc.

***- Complete building concept adaptation (system level)***
A commercial example of this is form the company Selvaag Bluethink who has developed the KBE (Lisp) based application “House Designer”. This is an example of how comprehensive this concept can be developed. Based on a draft layout, House Designer can suggest a very detailed design of the entire building. The profile of solutions is related to which rule sets that are activated. The rule sets can be different owner-defined requirements (standards / product types), different public standards (from different countries) and other requirements. (Opdahl and Olsen, 2009).

## 6. MODEL CONTENT CHECKING

The intention here is to examine the professional content in a BIM model for a specified use. There is no need for programming rules, just "filters" for reporting relevant information. This can be further analyzed in software as spreadsheets, word processors or databases. This gives this concept a large flexibility.

Today this can be done very easily and manually by model viewers, or with more complication using model servers. User friendly solutions between these solutions are needed.

***- Content of information compliance / IDM compliance***
The focus on this check is the content of information in the model compared to a requirement. This requirement can be defined in an IDM (ISO 29481-1:2010), in a BIM guide or specified as a separate project delivery. A general example is that all walls, windows, roofs and slab types shall contain information about energy performance (U-value), noise reduction and fire rating.

***- Client demand / space program / design program***
This is a variant of is based on comparing demands (constraints) from user specification with information in the model. Statsbygg - Public Construction and Property, Norway (2010) offered this as a service in phase 2 of the international architecture competition in the new National Museum in Oslo.

***- Not done checker / Next domain checker***
This is a version of the two examples above. Most checkers focus on what is in the model. One situation is that missing or forgotten technical equipments can give an impression that there is enough space). This can be done by replacing the demand list with a list of "default content" related to defined solutions. The default list can be based on experiences or just generally solutions (objects / attributes for defined solutions such as specified spaces; a surgery theatre (of specified type), occupy Xm$^2$ of equipment. This can be used for correctives of the space program.

***- Model comparison checking / Deviation analysis***
This model checking solution read the information in one model, and compares this with information in another model. The rule is based on compare demands. The rules is defining what one want to compare, such as; area or space, building or defined spaces, area of external wall, area of window, content of defined objects (HVAC). The results from this checking can be further analyzed.

***- Design process checking – Status***
This is a check of metadata related to the object. So far this information is not present in design software today, but a system for this was presented by Hjelseth (2009a) in the paper "Exchange of relevant information in BIM-objects defined by the Life cycle Information Model (LIM)". A design process, and its objects, is passing through different stages (ISO 22263:2008) from proposal to demolishing . The change of status can be checked for keep track of the process. This will also give improved control of clients demand and how these are satisfied (Kiviniemi, 2005).

***- Work progress checking – Schedule***
This metadata based concept for model checking can also be applied on the building site for checking the information in the real objects with the information in the schedule model. The challenge is to get real time data in a cost effective way. One solution is to use RFID (radio frequency identification) for automatic identification and data capture enables a real time logistics and makes is possible for having an “as-building” model (Hjelseth, 2010).

## 7. DISCUSSION

This paper use semantic arguments to propose the term model checking as identification for this domain of functionality. Many of the used terms as e.g. code checking has a limited scope, (here, checking only codes, not standards.) but are use for all types of checking. Whether the term model checking will be taken into the common language is dependent on a large number of circumstances outside this paper. However, some kind of systematic overview will be useful as counterweight to the mess in terms and brandings used today. In this respect we have introduced model checking as the term for this domain of function. The lack of formal definition in ISO etc. in this new area makes it easy to introduce own terms and brandings.

This paper do also propose four top level concepts of model checking. The question is whether the ontological structure is correct used itself, and if the number of four is complete as top level concepts. The ontology is based on the relation between four criteria; Intention, Result, Rule set and Type of product. We have been able to use this a taxonomy for classification within of all concepts (top level class) and in this respect find it useful for identification of meaning regardless of a term, brand or abbreviation.

The result of this approach based on its intention is that we need only four top level classes of model checking concepts. The limited number can be discussed, but should be kept as low as possible to reduce interference between the concepts. The number of four is the lowest number we have been able to define as concepts. In practical use will often lower level terms, or commercial branding, be used as description. We have for each concept described some sub classes for illustrating practical utilization. The proposed terms is only an description, not a definition, and multiple terms are therefore used. However, by use of the criteria for model checking, it should be possible determine which kind of model checking who is mentioned.

## 8. CONCLUSION

This paper gives an overview of model checking concepts based on its intentions. All concepts are based on an ontological foundation with a four level taxonomy consisting of *Intention – Result – Rule set – Type of products*, illustrated in figure 2 below.

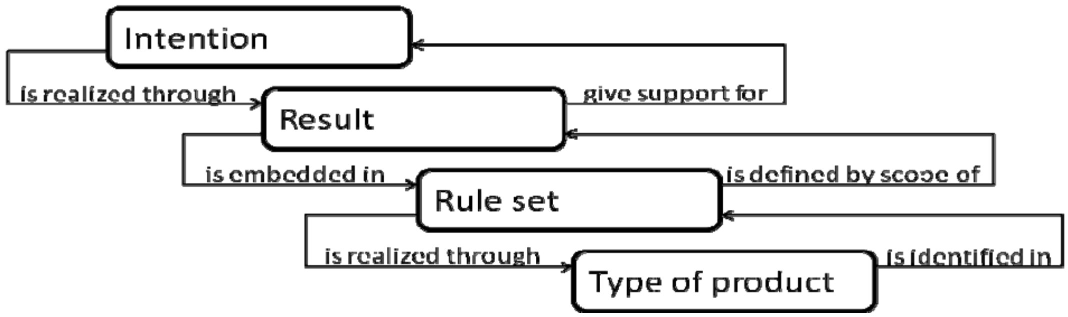


Figure 2: Ontology of model checking concepts

Based on "Intention" as the top level we propose following four concepts of model checking summarized in table 1 below.

Table 1: Concepts of model checking

| Intention | Result | Rule set | Type of product *) | Generic example |
|---|---|---|---|---|
| **Validating:** | pass/fail | is related to used standard / code / regulation etc. or parts above | is related to criteria in rule set | Clause = R or not(A) or not(S) or E |
| **Guiding:** | options and advice | | | set of possible R given A, S, E |
| **Adaptive:** | a modified model | | | one R given A, S, E |
| **Content:** | a filtered norm | | | set of relevant R given A,S,E |

*) can also be a materials, functions or other limitable subjects

R = Requirement, A = Applies, S = Select, E = Exception[2]

The proposed ontology for model checking can seen as a contribution to more precise use of model checking. This approach makes model checking as a part of a knowledge system (cf. figure 1.). Mixed systems of e.g. validating and guiding concepts can be developed for practical use, however the criteria to each concept remains unchanged.

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**Paper 2**

# Exploring semantic based model checking

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Co-author: Nick Nisbet.

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# EXPLORING SEMANTIC BASED MODEL CHECKING

Eilif Hjelseth, Ph.D. student, eilif.hjelseth@umb.no
*Norwegian University of Life Sciences (UMB), Dept. of Mathematical Sciences and Technology, Norway*
Nick Nisbet, Director, nn@aec3.com
*AEC3 UK Ltd, United Kingdom*

## ABSTRACT

This paper explores the foundation of semantic based model checking concepts. Development of computable rules in a pure semantic based concept is characterized by "soft coding" by following a pre-defined mark-up methodology for linguistic (text and numbers) analysis, organization, execution and reporting. The software programming for this can be done automatically or semi-automatically based on predefined procedures. This enables a person skilled in the AEC domain to develop applicable rules without support of programmers. The rules can be then be applied to the semantic content of a Building Information Model, typically in the IFC format.
Whether it is possible to develop a valid and reliable system applicable to rule sources (laws, codes, regulations and standards) depends on testing two key hypotheses:

The user's perspective is basis for the first hypothesis which says that a pre-defined semantic system or toolset can be used by person skilled in the AEC domain (not software programmer) to define rules. The second hypothesis proposes that a system for automatic, or semi-automatic, generation of applicable rule sets for software implementation can be developed.

**Keywords:** Model checking, semantic, BIM, IFC

## 1. INTRODUCTION

The facilities industry is highly regulated by a large number rules given by public laws, codes, and regulative, standards national and international levels which taken together identify what is permitted or recommended. User demands can also be considered as the same as rules. Rules can be complicated in itself and interlinked with other regulations or preconditions. This situation indicates a need for product model checking systems that can support the design process through into the entire facility life cycle. The question is if and how such a system can be designed to fulfill demands for time- and cost effective development and implementation into software. This paper will show that a semantic system based on four mark-up operators can provide a trustworthy result.  Due to logic consistency, we do also want to show that it is possible to auto generate software code from the marked up text.

## 2. MODEL CHECKING

We want to introduce automatic model checking tool to support the design processes. The term Model checking is used as a term for checking content of information in relation to defined requirements. Code compliance checking is classified as specific case where model checking "validates" the design. (Hjelseth and Nisbet, 2010).The challenge is how to do this in the best way overall. The obvious way is to have a procedure where an equally skilled person checks the design of the model, with or without some guidelines or checklist. This manually system is limited by the availability of such skills, and is error prone during repeated checking. Every checking exercise has relative high cost and takes time. Another solution can be replacing the expert with an expert systems based on AI (artificial intelligence) or KBE (knowledge based engineering) systems. These systems have large potential – but the cost and time for developing these systems dilute the benefit. An example of this is given by John F.

Sowa (2006) who refer to the Halo project where representing the knowledge in a chemistry book into an AI system was tried. The results were a score from 40% to 47 % correct and a cost of about $ 10.000 per page textbook. One explanation was the heterogeneity of the chemistry text leading to the “knowledge soup”. The “knowledge soup” arose for four reasons: a) Overgeneralizations, b) Incomplete definitions, c) Conflicting defaults and d) Unanticipated applications. Sowa further notice that experience shows that these exceptions and borderline cases result from the nature of the world, not from language or logic (Sowa, 2000).

## 3. SEMANTIC SYSTEMS

The focus on semantic systems is very high related to knowledge search. On the internet this new semantic approach is often called WEB 2.0. The semantic approach is also suitable for model checking, which is a kind of knowledge search supported by rules (also called methods, procedures, algorithms, formula and so on). By using a semantic approach we are able to handle two aspects related to:
a) Identification of the computable rules by a person with AEC domain skills
b) Implementation of applicable software code based on common predefined measures.

Regarding the first point, previously the development of rule sets for rule checking software has been vendor lead. This gives a “Black-box” solution and requires much testing prior to relying on the result. By empowering the domain experts we get a more transparent and direct method and can come much closer to the knowledge the rules are based on, reflecting the context definitions. In short, meaning is dependent on many factors, not just one. The correct interpretations of what might be understood, is obtained by using the viewers perspective. (Henderson (2010). An important aspect of checking in the AEC industry is that what is “checked” is very related and interacted with it “surroundings”. The source for rules (laws, codes, regulations, standards and so on) is also interlinked with each other. An AEC professional is far more skilled to appreciate this than a software developer.

The semantic ambiguity in the reference data complexity is decreased by use of;
- Dictionary; vocabulary, terms and definitions,
- Taxonomy; classes in sub-/superclass hierarchy,
- Ontology; constraints and connections.

Ideally, the vocabulary used by the domain experts would be drawn from an existing ontology. At this early stage, the process is being reversed and key concepts and properties are being identified during the tagging process. Lists of synonyms and shades of meaning that depend on context are being catalogued.

## 4. FOUNDATION FOR A MARK-UP LANGUAGE

Based on semantic theory (Sowa, 2000, 2006, 2007 and Tarski, 1935, 1944) it should be possible to develop a logic system with a finite domain and a structured language. The languages and semantics in standards are written in a defined way, and are suitable for translating into formal notation in a truthful way. An example is the ISO normative rules for structuring and drafting international standards in table 1.

Table. 1: Requirement, ISO Table H1 (ISO, 2004)

| **Verbal form** | **Equivalent expressions for use in exceptional cases** |
|---|---|
| **shall** | is to<br>is required to<br>it is required that<br>has to<br>only … is permitted<br>it is necessary |
| **shall not** | is not allowed [permitted] [acceptable] [permissible]<br>is required to be not<br>is required that … be not<br>is not to be |
| Do not use “must” as an alternative for “shall”. (This will avoid any confusion between the requirements of a document and external statutory obligations.). Do not use “may not” instead of “shall not” to express a prohibition. To express a direct instruction, for example referring to steps to be taken in a test method, use the imperative mood in English. Example: “Switch on the recorder.” | |

For “*Recommendation*, (ISO Table H.2) the ISO standards use the verbal form: *Should / should not*, for “Permission” (ISO Table H.3) the ISO standards use the verbal form: *May / need not*, and for “*Possibility and capability*” (ISO Table H.4) the ISO standards use the verbal form: *Can / cannot*, all with equivalent expressions for use in exceptional cases similar to Table H.1. (ISO, 2004). By use of semantic method it should be possible to develop a rule based version (“Rulish” version) ready for implementation into software. Laws and regulations also have a similar way of using modal auxiliary verb.

## 5. DEVELOPMENT OF SEMANTIC BASED RULES

Based on the theoretical foundation described below, there should be possible to develop a semantic based system for model checking who gives trustworthy results for use in the AEC knowledge domain. A semantic solution is more about a process than tools, where the process will capture the essence of a building code and convert this into a computable rule

Legislation and regulations typically present as apparently well-structured documents. Irrespective of the relative complexity of any particular document, it is possible and useful to identify the common constructs being described. It is proposed that regulations can be broken down into five fundamental concepts. These five concepts were elected to be most familiar to regulatory experts and designers, rather than to application or database analysts. The most general of these has been named the ‘check’ and typically demarcates a section of the regulation that is distinct and independent of any other. ‘Checks’ are often, but not necessarily, closely related to the named or titled sections in the document. It is a characteristic of regulations that every ‘check’ must be in some way satisfied.

A ‘check’ is not an indivisible (atomic) concept: it can be analyzed down further into four subsidiary constructs. The most obvious and most easily identified are the ’requirements’ as these are associated with the future imperatives ‘shall’ or ‘shall not’, it is required that a check contains at least one ‘requirement’. Secondly, there will be text that identifies the ‘applicability’ of the check. These are often compounded, for example ‘external windows’ which compounds the ‘external envelope’ concept with the ‘window’ concept. These phrases need not relate directly to the topic of the regulation or the topic of the overall check. For example, if a check applies in ‘seismic zone X’, this is a property of the building site, not of the structural integrity of a particular building component. In general, there will be one or more phrases defining the applicability. One similar but distinct case is where a ‘selection’ of alternative subjects is offered, for example ‘doors, windows and other openings’. Lastly, there may be one or more ‘exceptions’. These are the opposite of ‘applicabilities’, and conversely work by exclusion. To summarize, a regulation contains a number of ‘checks’, and each check contains a number of ‘requirements’, ‘applicabilities’, ‘selections’ and ‘exceptions’.

Actual checks may contain a number of requirements, applicabilities, selections and exceptions. It is important to identify how these combine. Requirements are typically cumulative; if there are several stated requirements, then it is to be expected that all must be satisfied. Similarly, applicabilities are cumulative and all must be met. However, if there are many exceptions or selections, then typically these are alternatives, and only one will be relevant. Using a short notation:

**R**equirement $R_0 = R_1$ *and* $R_2$ *and* $R_3$ *and…* $R_n$
**A**pplicability $A_0 = A_1$ *and* $A_2$ *and* $A_3$ *and…* $A_n$
**S**election $S_0 = S_1$ *or* $S_2$ *or* $S_3$ *or…* $S_n$
**E**xception $E_0 = E_1$ *or* $E_2$ *or* $E_3$ *or…* $E_n$

Sometimes more complex linguistic structures are encountered, usually reflecting more complex logical intentions. Methods for representing these have been developed, using subtypes of the four concepts. However complex any actual examples prove, standard logical calculus allows these to be expanded and manipulated, as shown in Figure 1.

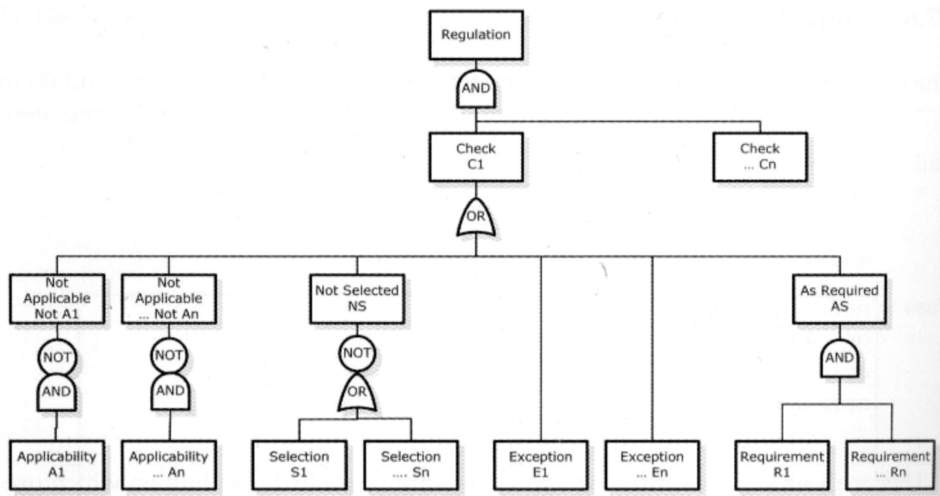



Figure 1: Applications use a logical expansion of the mark-up hierarchy.

The check, ($C_1$), is then equal to a logical combination of the ways of passing the check, which can also be summarized in a short notation.

$C_0 = R_0$ or not $A_0$ or not $S_0$ or $E_0$

The regulation is the logical combination of the distinct checks, which can also be summarized in a short notation. The argument is made more general by observing that most check clauses function as requirements.

$\text{Regulation}_0 = C_1$ and $C_2$ and $C_3$ and … $C_n$

Regulations can be grouped into rule-sets, representing a domain (field / area) which is to be checked. An example is accessibility for electrical or manual wheelchair.

## 6. SUGGESTION FOR A MARK-UP LANGUAGE

The language in a mark-up should be based on as few operators as possible, and must also used in a well documented and transparent way. Our suggestion is to use following operators; select, applies, requirement and exception. Applied on a text, the user highlights any phrase that means:

- more scope as a ‘select’
- less scope as an ‘applies’
- ‘shall’/’must’ etc as a ‘requirement’, (including alternative requirements)

• ‘unless’ etc as an ‘exception’, (including composite exceptions).

The relation between the operators and the original building codes in text is made apparent by a color system according to the mark-up language. An example of the mark-up operators and its related colors is software is illustrated in figure 2. The colors were chosen for acceptability for those with visual impairments.

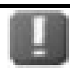
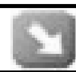
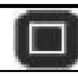
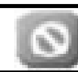
|  |  |  |  |
|---|---|---|---|
| Requirement {blue} | Applies {green} | Select {*red*} | Exception {*orange*} |

Figure 2: The four operators for rule development

Those four operators used for marking up text can be visualized by colors related to the operators, e.g. blue, green, red and orange. This gives the user an instant overview of what and how the rules are structured. The naming of the operator is specially chosen to correspond with the way standards, codes, regulative are written, which reflects natural language.

Requirement (R), Applicabilities (A), Selection (S) and Exceptions (E) constructs can be identically attributed to have a *topic*, a *property*, a *comparator* and a *target value*. The topic and property will ideally be drawn from a restricted dictionary composed of terms defined within the regulation and normal practice. The value (with any unit) may be numeric, whereupon the comparators will include ‘greater’, ‘lesser’, ‘equal’ and their converses. If the value is descriptive, then only the ‘equal’ or ‘not equal’ comparators are relevant. If the value represents a set of objects, then the comparator may be any of the set comparison operators such as ‘includes’, ‘excludes’.

## 7. EXAMPLE OF IMPLEMENTATION

The ICC SMART codes project can be used as an example of how this semantic concept can be implemented into software and applicable model checking. The components of a regulation are illustrated in table 2 by a rule on moisture control. The rule ‘applies’ on building elements. Based on the ontology, this also includes walls, windows, doors, ceilings, slabs and so on. Under ‘selected’ is the building element that has to be present. Without a wall, moisture control is not possible. Under ‘except’ is a number of conditions where this rule will not run, for example moisture is not a problem in defined areas of the country classified as climatic zone 1, 2 or 3. If the building elements are moisture proof, frost proof or condensation proof, moisture is of course no problem for the building elements. The resulting metrics are summarized in table 3.

Table 2: Example clause (based on ICC IECC 2006 502.5 Moisture control. (Mandatory)).

| **Rule source** | **ICC IECC 2006 502.5 Moisture control** |
|---|---|
| **Rule description** | All {*green/*}framed{*\green*}{*red/*} walls, floors{*\red*} and {*red/*}ceilings{*\red*} {*orange/*}not ventilated{*\orange*} to allow moisture to escape shall be provided with an {*blue/*}approved vapor retarder{*\blue*} having {*blue/*}a permeance rating of 1 perm{*\blue*} (5.7 × 10 –11 kg/Pa s m2) or less, when tested in accordance with the desiccant method using Procedure A of ASTM E 96. The vapor retarder shall be {*blue/*}installed on the warm-in-winter side{*\blue*} of the insulation. Exceptions: {*orange/*}Buildings located in Climate Zones 1 through 3{*\orange*} as indicated in Figure 301.1 and Table 301.1. In construction where {*orange/*}moisture{*\orange*} or its {*orange/*}freezing{*\orange*} will not damage the materials. Where other approved means to avoid {*orange/*}condensation{*\orange*} in unventilated framed wall, floor, roof and ceiling cavities. |

Table 3: Overview of mark-up in a rule for moisture control

| **Mark-up operator** | **Mark-up color** | **Identification of construction object** | **Property of object** | **Logic relation** | **Value** |
|---|---|---|---|---|---|
| **apply** | *green* | building element | construction | = | framed |
| **select** | *red* | wall | *(existence)* | = | *(true)* |
| **select** | *red* | floor | *(existence)* | = | *(true)* |
| **select** | *red* | ceiling | *(existence)* | = | *(true)* |
| **except** | *orange* | building element | ventilated | = | *(true)* |
| **except** | *orange* | site | zone | = | 1 |
| **except** | *orange* | site | zone | = | 2 |
| **except** | *orange* | site | zone | = | 3 |
| **except** | *orange* | building element | moisture proof | = | *(true)* |
| **except** | *orange* | building element | frost proof | = | *(true)* |
| **except** | *orange* | building element | condensation proof | = | *(true)* |
| **require** | *blue* | building element. vapor retarder | *(existence)* | = | *(true)* |
| **require** | *blue* | building element. vapor retarder | permeance | < | 1 |
| **require** | *blue* | building element. vapor retarder | location | = | warm-in-winter |

## 8. THE LOGIC OF SEMANTIC

There is no lack of sophisticated AI and expert systems. Some can even beat the world champion in chess, as when Gary Kasparov was beaten by IBM's Deep Blue in 1997 (Russell and Norvig 2010) However, the is a lack of time- and cost effective systems for development of computable rules for practical use. The challenge is within Einstein's famous quote: Make is as simple as possible, but not simpler. In our opinion the semantic approach does offer this change of paradigm. As we see form Peirce's truth tables for Boolean algebra where he introduce the if-then table. He also introduce the inclusive or instead of Boole's exclusive or. Peirce preferred to use the connected symbol –< to indicate that this is a single indivisible operation and not a combination of < and = .The different combinations are set up in figure 3 as Peirce's truth table for Boolean algebra (Sowa, 2000).

And

| × | 0 | 1 |
|---|---|---|
| 0 | 0 | 0 |
| 1 | 0 | 1 |

Or

| + | 0 | 1 |
|---|---|---|
| 0 | 0 | 1 |
| 1 | 1 | 1 |

Not

| − | |
|---|---|
| 0 | 1 |
| 1 | 0 |

If-then

| –< | 0 | 1 |
|---|---|---|
| 0 | 1 | 1 |
| 1 | 0 | 1 |

Figure 3. Peirce's truth table for Boolean algebra (Sowa, 2000)

Both Boolean algebra and semantic algebra have basis in natural language, but with some differences. The semantic approach uses four operators; **R**equirement, **A**pplies, **S**elect, **E**xception (RASE) to identify the natural concepts. Boolean uses three operators And, Or , Not (AON) to highlight the written words.

The "RASE" approach is analogous to Aristotle's analysis in ‘On Interpretation’ of normative sentences, where all sentences are classified as Universal or Particular, Affirmative or Negative (table 4) . Both grids organize normative statements, the difference being that Aristotle organized the grid by how they are expressed, we have organized them by how they combine;

Table 4: Aristotle’s normative sentences (Sowa, 2000)

| | **Affirmation** | **Denial** |
|---|---|---|
| **Universal** | Every A is B | No A is B |
| **Particular** | Some A is B | Not every A is B |

RASE can be logically transformed to AON, and vice versa. Table 5 is a matrix of the logical conjunctions for RASE, which confirms that there are exactly four concepts needed.

Table 5: Relation between semantic and Boolean operators

| | **-** | **not** |
|---|---|---|
| **and** | R | A |
| **or** | E | S |

For implementation, the use of the four semantic operators was preferred to having to introduce two operators, one list-based, one unary based, as required by AON. All four RASE logical operators act on a list of metrics. This makes the code to process them simple and consistent, even where individual metrics are allowed to have an UNKNOWN value as an alternative to TRUE or FALSE.

Experiences from a number of projects (ICC and GSA in USA, Byggforsk Knowledge systems in Norway) are that the operators correspond to our thinking (cognition) and support organizing of texts. Having a transparent interpretation makes it much easier to detect errors. This gives a more trustworthy result than a more sophisticated and generic system. The possibility for automatic generation for applicable software code is indicated by the relation to the IFC constraint model.

## 9. AUTOMATIC GENERATION OF APPLICABLE SOFTWARE CODE

The development of computable rules is enabled through a predefined semantic system. It will therefore be possible to make automatic generation of applicable software code. There is a 1:1 relation between the semantic operators and logical operators in software code identified by the mark-up. The markup XML is inserted into the original text.. The marked up document is then processed by a single recursive algorithm to convert this into a single computable rule that can be expressed in the IFC Constraint schema. The IFC Constraint schema is in effect a standardized computable rule format, usable by any rule engine capable of reading an IFC building model file.

## 10. USE OF THE LOGICAL CONSTRAINT MODEL

Alongside computable rules , the model to be checked must contain relevant information. The Building Information Model (BIM) is in practice represented by an IFC file. The IFC file format (IFC schema) is defined in the ISO standard ISO 16759  and contains over 700 objects. However, there are today some limitations in the scope of implementation of information capture in BIM based software. By increased utilization – and demand from the of AEC industry against the software developer, the lack if’ I’ in the ‘BIM’ will decrease. (Hjelseth, 2009a).

The demand for information in the IFC file will in some degree depend on what the specific rules request. We recognize that the IFC files typically contain a Coordination View (MVD) with information about project, site, building, stores, spaces, walls and slabs, beams, columns, footings, windows, doors and openings, mechanical, electrical and plumbing parts, and their relationships. Most of this is commonly produced in IFC compliant software already. In addition to this we recommend that the IFC file contain information about zone and system group definitions, ceiling elements, plenum spaces, elements and openings, type and layers of materials. An extended information set should contain some form of classification (IFC is a non-hierarchical schema) by use of

Omniclass and other regional systems. Information about the building should contain part building definitions, (apartment) and aggregate building definitions (campus). Information about shape of terrain and relationship to buildings should be included.

If the model does not contain sufficient information to evaluate a specific metric, then that metric will be deemed neither True nor False, but Unknown. The logical engine can identify the impact of the Unknown which may or may not, depending on the logical structure of the regulation, impact the status of the higher level objectives, right through to the regulation as a whole. Even if there is no BIM available, the logical statement can be used to control structured dialogues, by telephone or by web page with the user. For example, the ICC has demonstrated user interfaces and storefronts that will allow users to describe their building incrementally and apply automatic checking of defined codes and standards (Wix, Nisbet and Liebich, 2008).

## 11. USING THE IFC CONSTRAINT MODEL

Both simple and complex constraints can be captured using the IFC constraint sub-schema. This is done through the use of a constraint aggregation “IfcRelAggregatesConstraints” where the aggregation can be characterized by a logical AND, logical OR, logical NOTAND or logical NOTOR operators. This relationship is illustrated in figure 4.

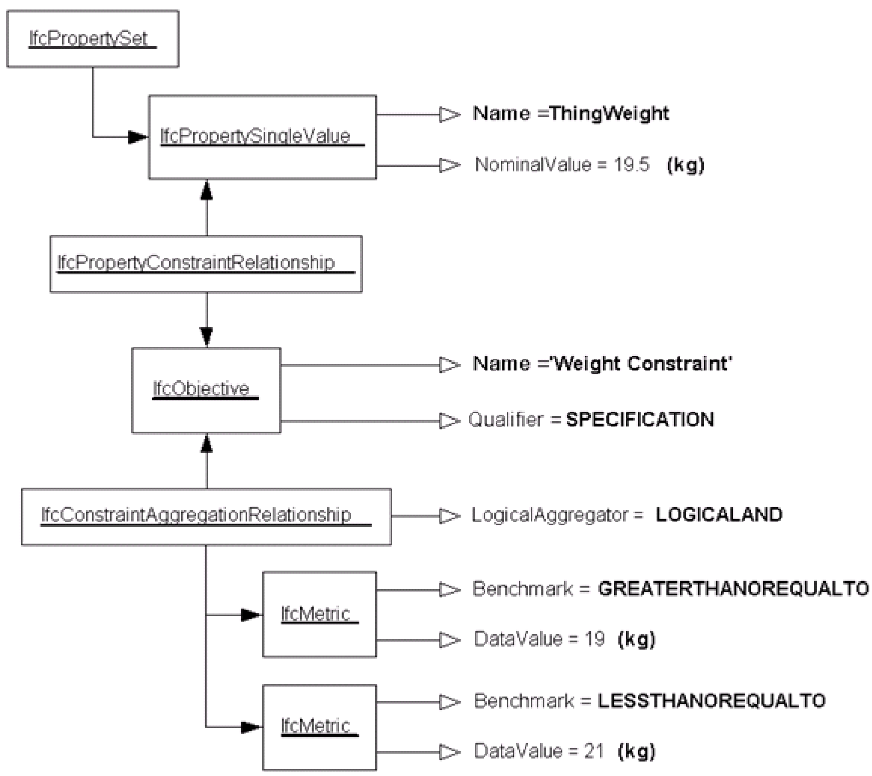



Figure 4: IFC Constraint Model

From the IFC2x3 Specification: "The example [...] shows how a constraint may be applied to a property within a property set. For simplicity, only the mandatory attributes are shown as asserted. It shows how a property 'ThingWeight' which has a nominal value of 19.5 kg has two constraints that are logically aggregated by an AND connection. One of the constraints has a benchmark of 'GREATERTHANOREQUALTO' whilst the second has a benchmark of 'LESSTHANOREQUALTO'. This means that the constraint must lie between these two bounding values. The relating constraint is instantiated as an objective named as 'Weight Constraint' and qualified as a SPECIFICATION constraint. The two related constraints are both specified as metrics since they can have specific values.

## 12. STANDARDS

The methodology has been described without many references to the underlying standards that make it practical and economic. In summary, W3C standards, and in particular XHTML, XML, XSLT and XLINK, allow the creation, presentation and interpretation of marked-up regulations. The general web infrastructure allows owners of documents to make them accessible dynamically in such a format without loss of control. ISO/PAS 16739:2005 "IFC2x Platform" allows all the major BIM applications to prepare descriptions of buildings in a form susceptible to automated checking based on IFCs. This means that the tools to actually generate a BIM that can be checked are already in daily use within the industry. It also provides a schema for the representation of the logical content of each regulatory framework, for use if the source regulations are not accessible. Lastly, ISO 12006-3:2007 "Framework for object-oriented information" provides an International Framework for Dictionaries (IFD) to manage the definition and sharing of common construction concepts independent of language and culture.

## 13. DISCUSSIONS

This paper attempt to verify two hypotheses. The first hypothesis states that use of four semantic mark-up operators; Requirement, Applies, Select, and Exception are sufficient for development of applicable rules from text such as regulations or standards. The evidence for this is based on chain of thought from philosophical and logical concepts from Aristotle to Boolean and Pierce by illustrating the strong similarities. Practical results from projects as ICC SmartCode have been successful but cannot provide absolute verification. It is accepted that the "generate and test" approach for verification does itself not give scientific evidence, just that all tested cases give an accepted result. Another aspect is if this semantic concept prefers a well defined structure of the text. If the text itself is very unstructured and unclear it may lead to instability in development of the rules. According to Tarski (1935, 1944) and Sowa (2000) the source of misinterpretation is in the formulation of codes and standard, and not in the proposed semantic concept. These preconditions is included in our verification, but we are sure that the closer the text of codes and standards follow the ISO regulative format, the more easily a trustworthy result for practical use is obtained.

The hypothesis about the possibility to auto generate applicable rule for software implementation is based on use of linking pre-defined software code to the test marked text by each of the four semantic operators. Based on the 1:1 relationship between mark-up and software code, the hypothesis can be regarded as verified. This is useful, but not sufficient to have a complete model checking system. The requirements for functionality in a model checking system is the foreseeable challenge in automatic collection for information from a BIM file in a defined format, e.g. IFC and its identification of objects and their properties and relationships.

## 14. CONCLUSONS

Semantic based model checking has potential to radically alter the cost/benefit balance for model checking tools We find it the two hypotheses proven by drawing up the direct connection they have to accepted philosophical and logic systems. Trustworthy rules can be specified from direct semantic interpretation of text by use of four semantic mark-up operators; Requirement, Applies, Select and Exception. We find it proven or at least made probable that this work can and should be done by AEC professionals, and not by programming experts. The connection between marked up text and generation of applicable software code is then automatic. This paper does not describe a complete model checking system, but verify principles as a foundation for systems for practical use.

## 15. FURTHER DEVELOPMENT

The semantic based system is according to Hjelseth and Nisbet (2010) able to handle a wide range of purposes as validating, guiding systems, adaptive and content based model checking. To date we have only applied the approach to fully normative documents that are expected to result in a pass or fail (validating model checking) . The authors believe that the approach can be expanded to include advisory documents where requirements, exceptions, applicability and selection are written with imprecision. This imprecision may affect the target values, the measured attributes, and the logical combinations of the metrics. However the appropriate flavors of 'fuzzy logic' should allow a single engine to process the uncertainty and give useful results.

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**Paper 3**

# Exchange of Relevant Information in BIM Objects Defined by the Role- and Life-Cycle Information Model

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# Exchange of relevant information in BIM-objects defined by the Role- and Life cycle Information Model (RIM/LIM)

Eilif Hjelseth
Norwegian University of Life Sciences, Norway (e-mail: eilif.hjelseth@umb.no)

## Abstract

*This paper focuses on how to specify relevant content of information in objects and object libraries for exchanging relevant and reliable information in BIM (building information model) based software.*

*There is a general lack of professional information in BIM based designs. The AECOO (architects, engineers, contractors, owners and operators) industry should therefore take the initiative for achieving a broad consensus about the specification of relevant information that should be standardized as content in the objects. Improved exchange of information in BIM based software will support integrated design and delivery solutions (IDDS.)*

*Objects / object libraries are proposed as the container for exchange of information. Software objects (doors, windows, walls) and object libraries (selection of objects) with specified professional information (measurements, performance; energy, fire resistance, noise reduction etc.) are called "BIM objects".*

*The "Role-and Life cycle Information Model" (RIM/LIM) concept is suggested as a framework for development (specification) of relevant information in different roles and phases of the building's life cycle.*

*A "BIM object information standard" can be based on the RIM/LIM framework. Content in the BIM objects can be included as specifications in IDMs (Information Delivery Manual) and BIM guides.*

**Keywords:** information exchange, standardization, BIM, LIM / RIM, AECOO

## 1. Introduction - Problems addressed

The exchange of relevant information in the AECOO industry (architects, engineers, contractors, owners and operators) is extensive. Use of IDDS (integrated design and delivery solution) based building design processes, which normally is based on a team of different actors and disciplines performing together, is increasing the demand for exchange of *relevant* information between the actors at the right time.

The development of BIM (Building Information Model) based software for the exchange of information represents a change from the traditional design process. BIM integrates geometrical representation (directly visible) with information (not directly visible). The focus in this paper is set on exchange of relevant content (or action against lack of content) in the objects (object libraries) in BIM based software. Even if we observe some variation between different architectural design software programs, the general observation is that the BIM files generally contains very little relevant professional information, such as e.g. thermal transmittance, acoustics rating, fire rating and/or environmental indexes. Documentation of what information is exported is usually absent, even if the software is marketed as BIM software, or labeled as IFC-compliant. A major challenge is therefore to remove the software developers undocumented "black-box" exchange of information, and instead move to a transparent exchange of information where the user knows exactly what information is exchanged – and that this information is relevant for the practical use and trustworthy decision making (Hjelseth, 2009).

# 2. Use of information in the AEC-industry

## 2.1 Tradition for utilization of new information

The increasing complexity of the built environments and the high number of roles in the design process involve new challenges in the logistics of information. Information exchange in previous times was based on a very small amount of formal exchange, and was more about the presence of the master-builder and his commands on site. There has been a development from the master-builder to the period when the architects became a separate profession.

Information exchange is today separated and handled separately using drawings, technical documentation, procurement specifications, legal documentation etc. It is questionable whether the ability to deliver information at the right time, in the right place and in the right quantity and quality has followed up. BIM is sometimes presented as the solution to the information flow. It is doubtful if this ICT technology itself will provide the relevant professional information. However, BIM - especially based on the IFC-format (ISO/PAS 16739:2005) is expected to have a positive impact on technical interoperability and software independency.

When we try to utilize information in BIM based systems, we should take into account the challenge to define and specify the relevant information. It is important that the AEC-industry control this process, not the software developers, even if it may be hard to reach consensus. A main purpose with information is to support the decision making in the design process. The possibility to carry through an interactive design process with a large number of actors with multiple revisions, handling the total life cycle, is a central aim of integrated design projects. More *relevant* information should enable the possibility to make better decisions in an earlier phase than those made traditionally. In this way improved exchange of information exchange can be expected to have a high pay-off.

## 2.2 Information is a relation to a purpose

The traditional sequence of: data – information – knowledge – wisdom, gives information a rank, but no definition. Gregory Bateson (1979) defines information as "*a difference that makes a difference*"; hence "*information is a relation*". Our interpretation is that information also can be interpreted as *"information is the relation between defined data and a defined purpose"*. This implies that without a specified purpose, one does not have information, only data. This perspective starts by defining what action you want to perform (method to use) – and then relates this to the information which is demanded. The result is a distillation of the *relevant* information.

According to Sowa (2000) is it crucial that the information exchange must be as clear and transparent as possible to avoid struggling with the "Knowledge soup" consisting of vagueness, uncertainty, randomness and ignorance.

BIM based design process is not drawing, but assembling and adjustments of a large numbers of different BIM-objects, as doors, windows, walls, electrical, HVAC components. The drawings are just a visual representation of geometry. BIM based design is in this perspective a process for modeling of information about building components.

## 2.3 Information exchange in *IDDS*

We want to introduce the framework for the CIB[1] committee named IDDS - integrated design and delivery solutions, which focus on the interactions between people, process and technology as illustrated in Table 1. (Kokkala, 2009).

*Table 1. The IDDS framework for people, process and technology* (Kokkala, 2009).

| **The problems** |
| --- |

[1] French: "Conseil International du Bâtiment" Full name: International Council for Research and Innovation in Building and Construction

| People | Process | Technology |
| --- | --- | --- |
| Lack of motivation for change<br>Lack of communication and trust<br>Gap between education and industrial requirements<br>Personal egos<br>Lack of holistic view<br>Islands of professionals | Not "why" behind process descriptions<br>Model not basis for contracts<br>Service logic missing<br>Multicity of issues and interdependency of actors<br>Model ownership | Information exchange across disciplines<br>Existing standards and technology hinder interoperability<br>Excessive and unrealistic expectations<br>Islands of automation |
| **The opportunities** | | |
| **People** | **Process** | **Technology** |
| Education by the people and for the people<br>Well trained, motivated and skilled workforce<br>Current market recession provides opportunities for skill tune-up<br>Multidisciplinary, distributed teams collaborating across organizational boundaries | Process modularisation<br>Automation to allow concentration on what matters instead of routines<br>Focus on results, not routines<br>Use of manufacturing knowledge<br>Common inter-organisational incentives<br>Shift from cost-driven processes to value provision | Interfaces to standards<br>Technology penetration through demonstration of benefit<br>Solutions form learning from "models"<br>Multiple user type and context specified interfaces and solutions<br>Adaptation not adoption<br>Creative use of new technology |

Integrated design and delivery solutions, IDDS is according to Kokkala (2009) defined as:

"Integrated Design and Delivery[2] Solutions use collaborative work processes and enhanced skills,

with integrated data, information, and knowledge management to minimize structural and process inefficiencies and to enhance the value delivered during design, build, and operation, and across projects" (Kokkala, 2009).

[2] Note that "Delivery" is added to this quote for update to the current scope of IDDS.

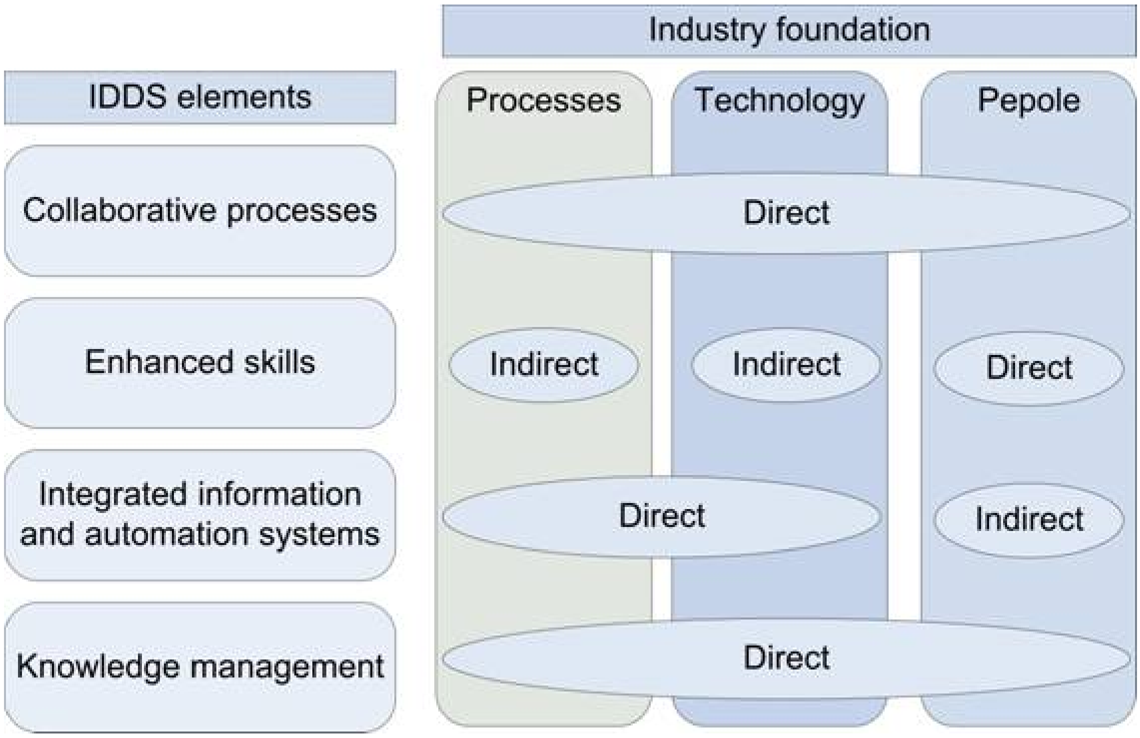


*Figure 2. Impact of four key IDDS elements on the industry foundation for processes, technology and people. (CIB-IDDS, 2009).*

We consider the BIM-objects / objects library to be an element of "Integrated information and automation systems". The proposed RIM/LIM framework can be considered as an element in Knowledge management.

## 2.4 Information Delivery Manual – IDM

The first part of the "IDM-standard", ISO 29481-1:2010, is now finalized as an international standards. This is a framework standard, describing a method for developing what information is required by whom and when, and in what form. It consists of three main components for information types and two components for rules:

***Information:***
- *Process maps* (PM) focus on the description of the flow of information and related business processes. Because of the fragmented structure in the AECOO industry, this will itself be very demonstrative. PM is independent of software.
- *Exchange requirement* (ER) focus on the documentation of the professionally relevant information needed for the specified methods etc. This part is independent of software.
- *Functional parts* focus on the mapping of ER against a technical schema such as IFC 2x3 and/or 2x4. This part is dependent on the file format to the software.

***Rules:***
*Business rules* (BR) and *Validation rules* (VR) are specifications of the behavior of information defined in the exchange requirement (ER).

Development of IDM within a defined topic and purpose (calculation method, use of a particular standard etc.) is recommended as a way of getting transparency in the information exchange. The professional information (ER) should be defined by selecting BIM-objects according to the Role- and Life cycle Information Model framework (Table 2) rather than being defined as single units. This can reduce time in development of IDM, lower for the barriers to participation, and motivate the reuse and re-modeling of IDM.

### 2.5 BIM-manuals

BIM-manuals can be used as mandatory guidelines for correct handling of information in a project. The development of BIM-manuals is in rapid progress. At the international standardization level is ISO/TC 59/SC 13 finalizing the ISO/TS 12911 Framework for BIM manuals (ISO, 2008). Governmental builders as GSA in USA (GSA, 2007), Senate Properties in Finland (Senate, 2007) and Statsbygg in Norway (Statsbygg, 2009) has developed their own BIM-manuals. AECOO organizations as bips in Denmark (bips, 2009) has developed their own BIM-manuals. An evaluation performed by Schijlen (2010) gives an overview of all these BIM-manuals. The BIM manuals can be developed to cover software related manuals, explaining how to set up the software (for specific purposes such as object libraries) and how to add and extract information.

## 3. Proposed solutions and frameworks

### 3.1 New – Need – Nice – Noise - Nonsense

The common tendency to regard more information as better can lead to information obesity and increased problems in practical use. Believing that the information needed for one purpose in an early phase can be directly re-used for other purposes and phases is potentially misleading. To distinguish between different types of information we use the terms; New, Need, Nice, Noise and Nonsense as illustrated in the list below.

***- New:*** Demands from new methods for use can require development of new information. An example of this is use of EPD, environmental product declarations. This has information in defined public databases (EPD, 2009) and the methodology is defined by ISO standards; ISO 14025:2006 Environmental labels and declarations -- Type III environmental declarations -- Principles and procedures and ISO 21930:2007 Sustainability in building construction -- Environmental declaration of building products.

**- *Need:*** Defined information to be as used as input in defined methods, standards calculations, algorithms, analysis etc. "Need" can also be called relevant information.

***- Nice:*** Estimated information to be used for known and new (unknown ad-hoc) methods This will result in collection and exchange of a large amount of information than necessary just to be sure (more information is better, uncritical "enrichment of model thinking". However, when a specific method is to be used, critical information can still be missing.

***- Noise:*** Information from all accessible information is collected and exchanged. No focus on specified use of methods etc (– all are good) for use. Too much irrelevant information in combination with some relevant information makes the information difficult to use.

***-Nonsense:*** Irrelevant information and duplicates, e.g. detailed and extensive information making wrong results.

Information content in both “New” and “Need” can be implemented in standards. This requests involvement from the AECOO industry to reach consensus about content of relevant information.

## 3.2 Information in BIM-objects

BIM is often defined as a 3-D model with information, but we think that the image; *"BIM is an information model with option for 3-D visualisation"* will provide a deeper way of understanding and motivate for new ways of use. The smallest units in the BIM model are the objects (of doors, windows, walls etc). Designing with BIM is not drawing, but assembling (and adjustment) of objects. All objects are in principle in 1:1 and are just a representation of the real world. The information is identical in a model presented in 1:50 scale where type of insulation (hard / soft) is shown in cross-section of the model and in 1:500 scales where the same wall is illustrated with double lines. The visualisation is managed by automatic rules, often according to CAD standards in the design software (ArchiCAD, Revit, VectorWorks, DDS etc.).

### 3.2.1 Information presented by visual observation (looking) at the model:

*Basic geometry* – This is most cases solved in objects, but with various levels of quality and details. When this is the sole aspect, use of native format or format for visualisation (3ds, VRML) gives best results. Parametric objects present a challenge, but special formats / domains as VDI 3805 format for HVAC has this option. Errors are visual, and correct solutions are often defined by CAD standards. Some software provides the option for calculated values for area and volume of the objects.

### *3.2.2* Information only available by active action to examine the content of information in the model:

At present, there is no common definition of professional content in objects, even if they are supplied in BIM or IFC compliant software. The main focus is on geometrical representation and visualizations. However there are often partial sets of informations associated to the objects:

*Identification* – Persistence of the identification is the foundation for effective design management. Identification of BIM objects has two sides: On the AECOO side, naming and description, which may include identification of the manufacturer and product code. On the ICT side uses a Global, Project or Context unique identifier. Systems and file based exchanges such as IFC provides GUID, but there is some challenges about "round trips" (when exporting and importing an IFC file, the GUID may get lost).
Bill of Quantity is an example where precise ID is used for bid calculations, production planning, procurement etc.

*Grouping* – The basic grouping is found in the inheritance of the BIM object which may correspond to an IFC class. There may also be classifications, and assignment to a specific layering. A particular instance is unlikely to carry all the classification that will be applied to the object during its entire lifecycle.

*Performance* – This is information about generic (and mandatory) properties of an object. Example is thermal transmittance, acoustics rating and fire rating of door, windows and walls. These properties are defined by standards. A subset of the performance properties are those used for the specification by designers and selection by contractors of the products which are supplied by sub-contractors and manufacturers.

*Status* - In design processes, and especially in *IDDS*, it is important to know the formal status of the objects. The design process is a decision process and knowing the status for all objects would be useful. The proposed status system has four categories, which can be related to roles and phases:

1) *Proposed:* component, element, building part etc. This will be the native BIM-object status.
2) *Decided;* and should not be changed, e.g. placement of columns (but exact material, amount of reinforcement and other consequences does not have to be decided). Include information (identification) about decision (role, constraints etc).
3) *Described;* the properties of the object (product) is specified. An agreement that "default" values shall be used is also possible.
4) *Built* indicates that the “object” has been assembled on the construction site.
5) *Replaced*, shows especially “historic” information, and will be useful in maintaining “as-built” models.

## 3.3 The Role Information Model - RIM

The scope of the proposed framework “Role Information Model” (RIM) is to define relevant information for defined roles (role is defined as a function being performed by and actor at a point in time in part 2 of the "IDM standard"[3] for development of BIM-objects. Examples of classification of roles in the Role Information Model are illustrated in the list of suggested roles below;

A) Architect
E) Engineer; SE) Structural engineer, EE) Electrical engineer, EH) HVAC engineer,
EF) Fire safety engineering
C) Contractor; CS) Structural contractor, CE) Electrical contractor, CH) HVAC contractor
O) Owner
F) Operator / Facility manager
L) Landscape architect
P) Public authority; PB) Building Authority, PC) Cultural Heritage
X, Y, Z) Others – to be specified.

An important aspect by the role information model for relevant information is to be aware of which type of information the user needs. The user is not the one who enters or produces the information, but the receiver of the information.

An example of this is when the architect need the surface and total thickness of the wall, while the structural engineer needs the reference model, where the wall is showed as lines and arrows (forces) and the energy consultant needs the detailed model with information about all components for the wall. (bips, 2010).

## 3.4 The Life cycle Information Model - LIM

The scope of the proposed framework “Life cycle Information Model” (LIM) is to be used for development of content of relevant information in BIM-objects. The content of information in the BIM-object is related to the phases of the life cycle of the building. The phases used in LIM correspond to the phases defined in ISO 22263:2008 “Framework for management of project information”, illustrated in table 2. In addition to information about performance and status, properties defining craftsmanship and other properties can be included. The recommendation is to keep the list of mandatory properties as small as possible to meet the relevant and most used methods.

[3] ISO/WD 29481-2 Building information modeling -- Information delivery manual -- Part 2: Management communication

## 3.5 The Role-and Life cycle Information Model framework

The previous described RIM and LIM framework can be combined to an interlinked *"Role- and Life cycle Information Model"* (RIM/LIM) framework for development of specification of content in the "BIM-objects. In contradiction to the “enrichment of the model” where more information is synonymous with better - leading to information obesity, the RIM/LIM focuses on the relevance of information relation to purpose. The Role- and Life cycle Information Model uses four major phases and a project dependant number of roles for defining professional content;

*Table 2. Role- and life cycle information model framework*
*Life cycle phases and stages built on ISO 22263:2008.*

| | **RIM** | **LIM** | **Sub-classes** |
|---|---|---|---|
| **BIM ordering** | **Primary role**<br>secondary roles | **Phase** | **Stage** |
| - Demand BIM | **O) Owner**<br>A) Architect<br>E) Engineers<br>C) Contractor | *Pre-project phase* | 0) Portfolio requirements<br>1) Conception of need<br>2) Outline feasibility /<br>3) Substantive feasibility |
| - Draft model | **A) Architect**<br>E) Engineers<br>C) Contractor | *Pre-construction phase* | 4) Outline conceptual design<br>5) Full conceptual design<br>6) Coordinated design (and procurement) |
| - Detail model | **C) Contractor**<br>E) Engineers | *Construction phase* | 7) Production information<br>8) Construction |
| - As-built model | **C) Contractor**<br>E) Engineers | *Post-construction phase.*<br>*- hand-over*<br>*- use of the building* | 9) Operation |
| - Facility management | **F) Facility manager** | | 9) Maintenance<br>10) Disposal |

The RIM/LIM framework defines the mandatory information for a defined type of object for a defined stage and role in the building process.

Table 2. illustrates a way to assess BIM-objects / BIM-libraries with relevant content of information. A BIM-object / BIM-library can contain information for one or more stages and roles.

**Selection of BIM objects**
The number of BIM-objects with variants may be very large. For use in a project one may "select" (download and install) a collection of relevant objects. This object library can be defined by the stakeholders in the design process. The contractor will often play a central role in this selection (dependent on type of contracts)

**The quality of information**
The RIM/LIM offers a standardized framework for collective use. The values of the information can either be pre-defined or left open for other phases or roles to decide. Who is responsible for which information can be managed by BIM-manual, IDM's and/or contracts. Pre-defined information can be quality assured by neutral (certification) organizations. This will enable trustworthy estimations in current and future phases. According to Hjelseth and Nisbet (2010) the content of information and its properties / values can be automatically verified by use of model checking system.

**Development of BIM-objects**
From a technical point of view, adding the program lines in the BIM-objects for relevant content of professional information is expected to imply marginal extra cost. This includes also implementation of Property set (PSet) from IFC schemas etc. It should be expected that development and distribution of BIM-objects from different software will maintain the same pattern as for model objects / object libraries today. This indicates that the change from using objects without professional information to use of BIM-objects is likely to be implemented in the AECOO industry.

# 4. Practical suggestion to solutions

## 4.1 Development of solutions (deliveries)

*Standard* - The information in BIM-objects / object libraries should be defined in ISO or national standards. The "*BIM-object information" standards* should contain lists of both mandatory and optional information according to the RIM/LIM framework (table 2.). For ensuring that the information is as relevant as possible, the standardisation work should be performed by experts from the AECOO industry, and with far less dominance from software industry. The BIM-object standard could be provided as a series of parts for covering all the different kinds of building objects and disciplines.

- *Development* – Development of the BIM-objects can still be performed by the same actors who provide model objects today. The only difference is that the providers now include professional information according to the BIM-object information standard. They still maintain their visualization features and profiling of own products. The software developers could facilitate this by including a “BIM-content” tab to the object property features. In addition to the generic models included in software, manufacturers of construction elements offer a wide range of objects for free use. It can be expect that manufactures that offer “BIM certified objects” will be preferred, and this will gain a swift implementation of the information elements into their existing objects of products.

- *Certification* – For some types of BIM-objects such as wall, window, doors etc. there is a close relation between properties such as thermal transmittance, acoustics rating and fire rating. A certification system can be established to ensure logical relevance and validity of information of the professional content.

## 4.2 ICT technical solutions

There is a large number of technical solutions for object libraries and exchange of information as IFC (ISO/PAS 16739:2005), PLIB (ISO 13584 Parts library series) and STEP (ISO 10303 Product data representation and exchange series), however these is normally not focused on content of information (what) but on how to exchange data.

We want to introduce a low level technical solution by suggestion increased utilization of the objects in BIM based software. There is of course no contradiction to introduce the RIM/LIM concept into more "complicated" technologies.

Correct handling of professional information is critical, and must be handled by domain experts. One issue who illustrates this was found in the IFC 2x3 and 2x4 schema for handling of BACS related information. BACnet is a communication protocol standard for building automation and control systems (BACS, 2010). According to BACS-expert and project manager Knut Loe in Standards Norway (Loe, 2010), is most of the property sets defined correctly, but some properties is used wrongly, and other often used properties is missing. This makes IFC use of BACS related information not yet fully trustworthy.

## 4.3 Examples of practical use – The "SPie-project"

We want to use the Specifiers’ Properties Information Exchange (SPie) (East and Nisbet, 2010) as example for our view for concepts (framework) for exchange of information. This initiative was launched by the US Army Corps of Engineers ERDC, and adopted by the National Institute of Building Sciences (NIBS). It recognized that the primary use case for information rich BIM objects arises from the specification/selection process. This process spans many actors and life cycle stages, and matches generic functional requirements against specific manufacturers’ product data. At early stages it may be sufficient to know that there exists at least one product, or a choice of products that meet the specification criteria. The pre-requisites for moving from paper and image based processes is the use of existing international standards. The format and facilities for identification and grouping available in the IFC model were adopted. Existing recommendations from buildingSMART were adopted. However the identification of the key properties for the specification/selection process demands the involvement of specification experts and the trade associations. This expertise includes regional best practice. Trade associations have a key role in achieving consensus across manufacturers. In the US NEMA (National Electrical Manufacturers Association) have shown strong leadership and other sector associations are now following. Once this process is established, it is anticipated that further performance data, such as that required for performance simulation will be added. Other use-cases, such as submittal approvals, warranty tracking and maintenance procedures will be added to ensure compatibility with COBie (Construction Operation of Buildings information exchange). In Europe, the most pressing use-case is the assessment of “cost, social and environmental impact”.

# 5. Discussions

This paper started with focusing on the basic of information exchange, and ended up with a practical solution on something one should believe was solved a long time ago. BIM is fundamentally about supporting the exchange of information and used wisely it should increase the gap between all roles in the AECOO industry. It can therefore appear strange that there are so few options for entering professional information in BIM based software: “Where is the I in BIM?” is therefore a relevant question.

One aspect is the general lack of demand for information. This has a number of causes built on no demand for not existing solutions, who again has background in establish attitudes for design with much focus mostly on visual effects, and little focus of information as an asset.

Technical can the objects of today easily be extended with information. This identifies two problems: What information is relevant and how can other utilize this information for further works?

The challenge is that the answers are interlinked to give improvement. The RIM/LIM framework can therefore be regarded as an initiative to a holistic approach to solve the problems with exchange of information in the AECOO industry. This can imply that the RIM/LIM concept must be further developed or adjusted. Here can the IDDS concept that focus on the relations between people, process and technology give a systematic approach to this complex problem.

There is a lack of standards and contracts for specification of information exchange. One example is that standards for BIM guidance at international and national level are missing or limited. On company- / organizational level we see that public builders like GSA in USA, Senattee in Finland, Statsbygg in Norway, bips in Denmark. buildingSMART in Germany has developed BIM guidance's.

One other explanation can be found in the business model; input of information does not give identified benefit for the one who produce the information – only the receiver.

Limited use of *IDDS* with its demand for information exchange can be another reason. A common interest to develop a BIM-object standard could be the first step. If, or when, the AECOO industry can put forward a defined demand for content “BIM-objects” – expressed in a “BIM-object information standard – it is likely that the software developers will invest the marginal effort to implement these properties. However, if no consensus in the AECOO industry, it is likely that a lot of proprietary ad-hoc solutions will emerge, and the priority of a formal standardized solution will suffer.

The RIM/LIM framework is based on an attitude that solutions based on standard gives the best solutions. This can result in very rigid and static solutions, and can reduce flexibility and alternative development. So far this does not seem to be a relevant drawback compared to the advantages of having some limited, but relevant information.

# 6. Conclusions

The proposed “Role- and Life cycle Information Model” (RIM/LIM) can be used as a framework for specifying the relevant information in BIM-objects according to its use in different roles and phases of the life cycle. The RIM/LIM represents a cross-over solution and has references to the IDDS concept for interaction between people-process and technology.

The lack of defined information in model objects in BIM based software limits the utilization of information in the design process in general and *IDDS* in special. The limited content of information objects (object libraries) has a connection to the absence of consensus about what type of information should be exchanged. The AECOO industry (people) should therefore take initiative to start a standardization process (process) for defining relevant information to be exchanged in the objects (technology) in BIM based software The BIM standards should contain definitions of mandatory and optional information related to the different roles and phases in the building process through it's life cycle.

Experiences from the SPIE, (Specifiers’ Properties Information Exchange), project illustrates the advantages of using a systematic and specified system for exchange of information related to products. This concept is equivalent to the RIM/LIM framework proposed in this paper.

There are to day a lot of software developers and manufactures that offer (often for free) objects for BIM based software. The ICT technical effort to extend the model objects to BIM-objects is regarded as minor. With a standard on place and demand from the marked, one can be assumed that content of relevant information will be implemented into objects – "The BIM-objects".

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**Paper 4**

# Capturing normative constraints by use of the semantic mark-up RASE methodology

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# CAPTURING NORMATIVE CONSTRAINTS BY USE OF THE SEMANTIC MARK-UP RASE METHODOLOGY

Eilif Hjelseth, Ph.D. student, eilif.hjelseth@umb.no
*UMB / Department of Mathematical Sciences and Technology, IMT, Norway*
Nick Nisbet, Director, nn@aec3.com
*AEC3 Ltd., UK*

## ABSTRACT

The AEC industry is highly regulated by a large number of rules given by public laws, codes, and regulative standards at both national and international levels. The relevant information in these documents need to be captured as rules for model checking in a time and cost effective way. The foundation for the RASE concept is using mark-up based on the four operators; requirement (R), applicabilities (A), selection (S) and exceptions (E) on normative text. The RASE technology has been tested on following three categories of documents: standard (case: NS 11001-1.E:2009 Universal design of building constructions - Part 1: Work buildings and buildings open to the public), standards with tables (Dubai regulations) and guidelines (case: GSA court design guidance document, USA). In each case expectations have been documented using free prose. On examination, the key clauses and phrases can be identified along with their role, allowing a testable, logical statement to be generated. The logical statement is then ready to be used by a compliance-checking engine to apply tests to a description of the facility. The results indicate that the RASE methodology can operate on a different types of normative documents with a trustworthy results.

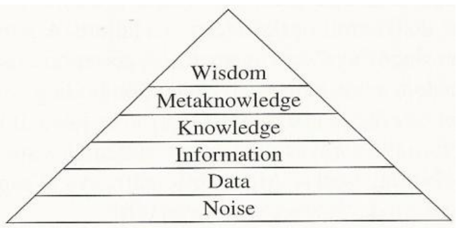
**Keywords:** Knowledge representation, Ontology, Semantics, Model checking, Decision support.

### 1.1 Problem status

The AEC/FM (architects, engineers, contractors, facility management) industry is highly regulated by a large number of rules given by public laws, codes, and regulative standards at both national and international levels. The question is how these normative documents can be captured as rules for automatic or semi-automatic model checking in a time and cost effective development and implementation into software. We see from the history of AI (artificial intelligence) and KBE (knowledge based engineering) and KM (knowledge management) that capturing information in a meaningful and trustworthy way has not been a straight-forward process, as the content increases (Russell and Norvig, 2010). We conclude that a wide spread use has not been reached and the expectations regarding semantic web has not moved forward as expected.

### 1.2 Principles for capturing knowledge

However, if we take a more direct and purpose driven approach, trustworthy results are possible. Hjelseth and Nisbet (2010) verified the fundamental principles for the four logical operator based RASE concept. We will in this paper capture from three different type of sources which in the next stage can be used in BIM based model checking systems. The RASE concept will according to figure 1 contribute with an alteration from information to metaknowlege.




**Wisdom**: Using knowledge in a beneficial way
**Metaknowledge**: Rules about knowledge
**Knowledge:** Rules about using information
**Information**: Potentially useful for knowledge
**Data:** Potentially useful information
**Noise:** No apparent information

Figure 1: The pyramid of knowledge. (Giarratano and Riley, 2005).

> *"Human knowledge is a process of approximation. In the focus of experience, there is comparative clarity. But the discrimination of this clarity leads into the penumbral background. There are always questions left over. The problem is to discriminate exactly what we know vaguely."* (Whitehead, 1937)

RASE is a semantic based concept for transforming normative documents into a singel well-defined rule which can be implemented into BIM / IFC based model checking software. The increased use of BIM enables the rules to apply in the information already captured in BIM models from many different design applications. Execution / implementation of rules in a model checker demands an unambiguous interpretation. We will in the following part will illustrate some general fundamental problems in text analysis and demonstrate that these can be solved or evaded by use of the RASE methodology. Our experiences indicate that RASE can also contribute to clearing up professional understanding of normative documents as standards, building codes etc. This will also influence on the challenge with performance based vs prescriptive defined regulations.

## 1.3 Knowledge soup

Knowledge soup is a concept develop by John F. Sowa (2000, 2004). It states that the complexity does not arise from the way the human brain works or the way that natural languages express information but rather from over-generalizations, abnormal conditions, incomplete definitions, conflicting defaults and unanticipated applications. These exceptions and borderline cases result from the nature of the world, not from any defect in natural language. We present in Chapter 2.2 three principles; Translate, Transform and Transfer for handing of these issues (Hjelseth, 2009). Tarski (1944) states that within a delimited domain, it is possible to achieve consistency and precise understanding. We are operating on normative documents within the building and construction domain.

## 1.4 Ontology

There are many definitions for "ontology". Schalkoff (2011) defines ontology as: "An ontology is a formal characterization of concepts in a domain of discourse". Some of the reasons to develop and ontology is to capture domain knowledge. Further can it be used to visualize, manipulate, reuse, and update or extend the representation. This may lead to an alternative, practical, and functional definition for an ontology: a way for a community to agree on common terms and structure for representing knowledge in a domain. A RASE rule can be considered as an exchange requirement. In the current example, both the rules model and the facility model are represented in the IFC schema. This approach has allowed applications such as Jotne EDM, Solibri and Singapore ePlanCheck to be adapted to use the rule model, re-using the IFC read/write capabilities already supported.

The IFC Product sub-schema represents the facility as a highly interrelated network of objects, such as walls, ramps and spaces. In contrast, the IFC Constraint sub-schema represents the logical structure of a normative document as a strict hierarchy of objectives. At the highest level, the primary objective is the satisfaction of the whole. This objective is then defined in terms of subsidiary objectives relating to distinct topics and their expression as requirements, exceptions, applicability and selection. At the lowest level the constraints are discrete metrics which carry testable expressions.

The constraint model is therefore a highly structured representation of the original text. However, the logical structure and each discrete metric have a direct line of derivation from the text and mark-up. This ensures that constraint model is recognizably and demonstrably correct. A reverse mapping can also be applied to the constraint model to construct free prose, though currently the re-constituted text is stylistically monotonous.

## 2.1 RASE theory

It is a characteristic of regulations that every 'check' must be in some way satisfied. The most obvious and most easily identified are the 'requirements' as these are associated with the future imperatives 'shall' or 'must' 'requirements'. It is required that a check contains at least one 'requirement'. Secondly, there will be text that identifies the 'applicability' of the check. These are often compounded, for example 'external windows'. These phrases need not relate directly to the topic of the regulation or the topic of the overall check. For example, if a check applies in 'a seismic zone', this is a property of the building site, not of the structural integrity of a particular building material. In general, there will be one or more phrases defining the applicability. One special but distinct case is where a 'selection' of alternative subjects or more 'exceptions'. These are the opposite of 'applicability', and conversely work by exclusion. (Nisbet, Wix and Conover, 2008). The RASE mark-up language uses the following four RASE operators: 'requirement' 'applies, 'select', and 'exception'. Applied on a text, the user highlights any clause or phrase that means:

- 'shall'/'must' as a ***'requirement'***, (including alternative requirements)
- less scope as an ***'applies'***
- more scope as a ***'select'***
- 'unless' as an ***'exception'***, (including composite exceptions).

The relation between the operators and the original building codes in text is made apparent by a colour system according to the mark-up language. An example of the mark-up operators and its related colours is software is illustrated in figure 2. The colours were chosen for acceptability for those with visual impairments.

| | | | |
|---|---|---|---|
| Requirement {blue} | Applies {green} | Select {*red*} | Exception {*orange*} |

Figure 2: The four RASE operators for rule development (Hjelseth and Nisbet, 2010a).

The four RASE operators used for marking up text can be visualized by colours related to the operators, e.g. blue, green, red and orange. This gives the user an instant overview of what and how the rules are structured. The naming of the operator is chosen to correspond with the way standards, codes, regulative are written, which reflects natural language.

The marked-up Requirement (R), Applicabilities (A), Selection (S) and Exceptions (E) clauses will contain phrases. The four types of phrases can be identically attributed to have a topic, a property, a comparator and a target value. The topic and property are ideally be drawn from a restricted dictionary composed of terms defined within the regulation and normal practice. The value (with any unit) may be numeric, whereupon the comparators will include 'greater', 'lesser', 'equal' and their converses. If the value is descriptive, then only the 'equal' or 'not equal' comparators are relevant. If the value represents a set of objects, then the comparator may be any of the set comparison operators such as 'includes', 'excludes' (Hjelseth and Nisbet, 2010a and Nisbet, Wix and Conover, 2008).

## 2.2 Methods for "normative-isation" of text.

### 2.2.1 General precondition

Developments of rules are based on interpretation of normative text. The RASE concept is optimized for this purpose. For handling of variation in text, we introduce three principles; Translate, Transform and Transfer for handing of semantic issues.

### 2.2.2 Translate

When presented with a normative text with clear metrics, one will get at direct match from original text into mark-up with the "RASE-operators" (Hjelseth, 2009).

### 2.2.3 Transform

However, not all code related text, even standards is suitable for this . Where the individual metrics are ill-defined, or the text is poorly drafted, then the process of mark-up will expose this. Unstructured or "blurry" text can be reformulated based on its intentions. If the text is redrafted, then the mark-up process can continue, but the results will be based on the re-formulation. The change has occurred in the source text, not in the transformation process. This ambiguity is particularly common in Guidance documents, one of the four types or model checking concepts stated by Hjelseth and Nisbet (2010 b), where the designer is expected to consider alternatives and preferences outside of the text. These rules can also be source for "Guidance based" model checking by presenting options and advice. The intention by explicit use transformation of the text source is to increase the number of rules which can be extracted for the original text. Because RASE give a explicit documentation, this will be transparent when used in model checker software.

### 2.2.4 Transfer

However, sometimes the original text is formulated in way where transformation does not give a trustworthy result in a model checker. This will sometimes be the case with general parts or statement of general principles on high level: the solution should be environmentally friendly, user friendly etc. It is important that these aspects of the original document are identified and information about this is presented for the user so it can be interpreted manually by a professional (Hjelseth, 2009).

### 2.3 **RASE technology**

RASE is based on utilization four operators defining a predefined and uniform action. This enables automatic /semi-automatic transformation into software code. The technology presented in this paper transform the mark-up from the operators into html-tags. The software is developed by Nick Nisbet in AEC3 Ltd and consists of a graphical interface, and the transform to a structured constraint model.

## 3 TEST APPROACH AND METHODS

The tests were applied to a normative regulation using prose, a normative regulations using a mixture of prose and tables and finally to any advisory 'guideline' document. In the examples, the original text is shown, followed by the mark-up. We then give a summary of the testable metrics and show the result of re-constituting the text from the logical statement, as evidence that the interpretation is correct.

### 3.1 **Test Case: Norwegian accessibility standard, NS 11001-1:2009**

Many jurisdictions in Europe and North America have introduced accessibility standards, with their focus on the accommodation of users with of ambulatory disabilities. An example clause which considers both spaces and solid building fabric is considered here. We use Clause 5.2 from "NS 11001-1.E:2009 Universal design of building constructions - Part 1: Work buildings and buildings open to the public" as an example:

> *5.2 Dimensioning an access route to a building*
> *The access route for pedestrians/wheelchair users shall not be steeper than 1:20. For distances of less than 3 metres, it may be steeper, but not more than 1:12.*
> *The access route shall have clear width of a minimum of 1,8 m and obstacles shall be placed so that they do not reduce that width. Maximum cross fall shall be 2 %.*
> *The access route shall have a horizontal landing at the start and end of the incline, plus a horizontal landing for every 0,6 m of incline. The landing shall be a minimum of 1,6 m deep.*
> *Minimum clear height shall be 2,25 m for the full width of the defined walking zone of the entire access route including crossing points.*

Figure 3: The regulation

In the original text, it may not be obvious that the overall applicability expressed in the title carries down into following sentences. The second sentence is actually an exception to the first. The mark-up is shown as seen in the mark-up application in figure 4 and in a short form in figure 5.

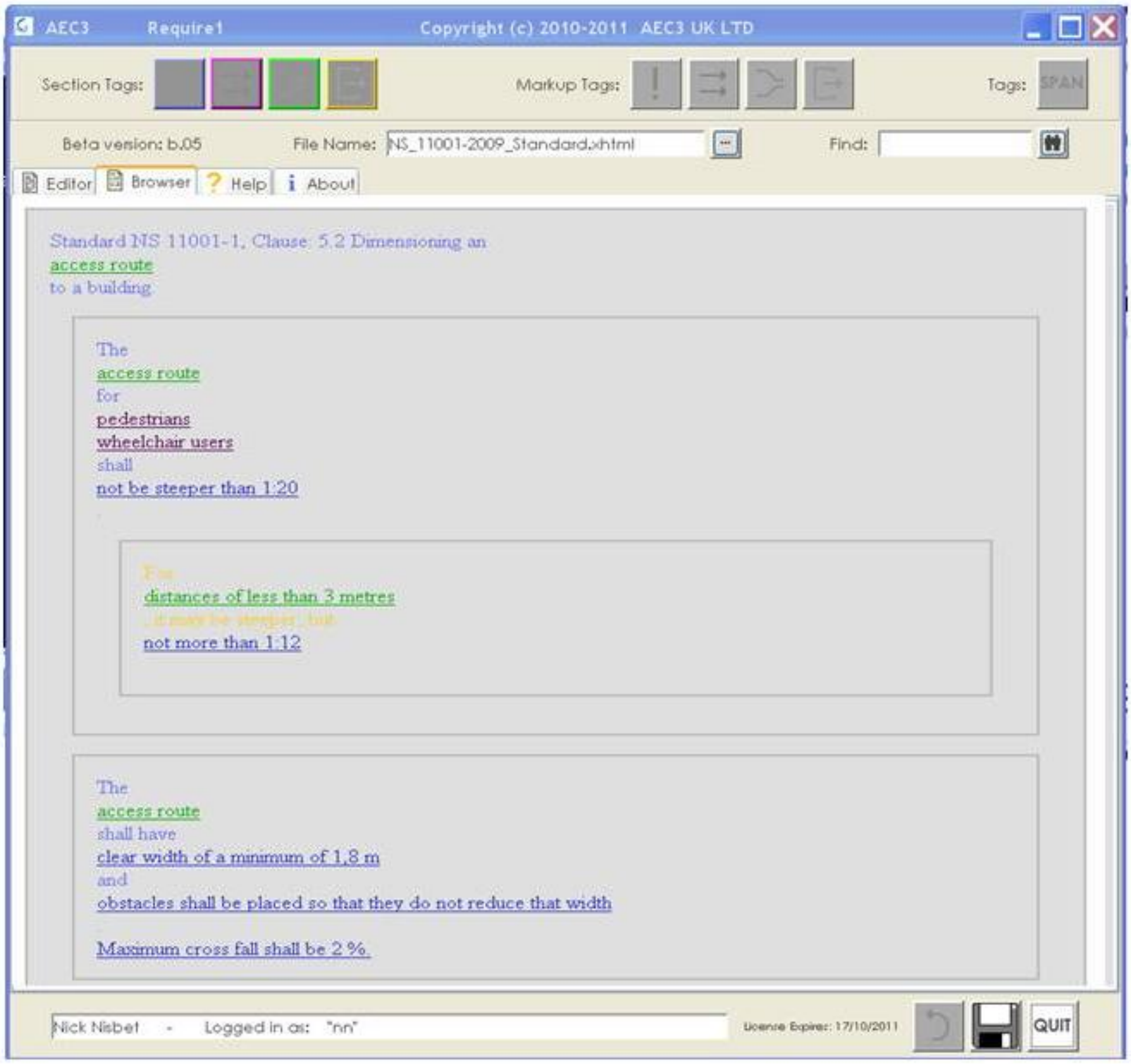



Figure 4: RASE mark-up by use of Require1 application. © AEC3 UK ltd

The application uses standard style-sheets to render the text with or without colour or tags shown. The underlying mark-up is shown in figure 5.

***<R>Standard NS 11001-1, Clause: 5.2 Dimensioning an <a>access route</a> to a building***
*<R> The <a>access route</a> for <s>pedestrians</s><s>wheelchair users</s> shall <r>not be steeper than 1:20</r>. <E>For <a>distances of less than 3 metres</a>, it may be steeper, but <r>not more than 1:12</r>.</E> </R>*
*<R>The <a>access route</a> shall have <r>clear width of a minimum of 1,8 m</r> and <r>obstacles shall be placed so that they do not reduce that width </r>.<r>Maximum cross fall shall be 2 %.</r></R>*
*<R>The <a>access route</a> shall have <r>a horizontal landing at the start and end of the incline<r>, plus <r>a horizontal landing for every 0,6 m of incline</r>. <r>The landing shall be a minimum of 1,6 m deep.</r></R>*
*<R><r>Minimum clear height shall be 2,25 m </r>for the full width of the defined walking zone of the entire <a>access route</a> including crossing points. </R></R>*

Figure 5: The underlying mark-up tags (‘R/A/S/E’ tags for clauses and ‘r/a/s/e’ tags for phrases.

In this presentation, objective clauses are shown here delimited by 'RASE' tags and metric phrases are delimited by 'rase' tags. Figure 6 summarises the phrases used with their equivalent object expressions.

| Metric phrase | Type | Object | Property | Comparison | Target | Unit |
|---|---|---|---|---|---|---|
| access route | applicability | space | usage | includes | access | |
| pedestrians | selection | space | user | includes | pede-strian | |
| wheelchair users | selection | space | user | includes | wheel chair users | |
| not be steeper than 1:20 | requirement | ramp | slope | more than | 20.000 | |
| distances of less than 3 metres | applicability | ramp | length | less than | 3.000 | m |
| not more than 1:12 | requirement | ramp | slope | more than | 12.000 | |
| clear width of a minimum of 1,8 m | requirement | ramp | width | more than | 1.800 | m |
| obstacles shall be placed so that they do not reduce that width | requirement | ramp | obstructed | equals | FALSE | |
| maximum cross fall shall be 2 % | requirement | ramp | cross fall | less than | 2.000 | % |
| a horizontal landing at the start and end of the incline | requirement | ramp | has landings | equals | TRUE | |
| a horizontal landing for every 0,6 m of incline | requirement | ramp | landing interval | less than | 0.600 | m |
| the landing shall be a minimum of 1,6 m deep. | requirement | landing | width | more than | 1.600 | m |
| <minimum clear height shall be 2,25 m | requirement | space | clear height | more than | 2.250 | m |

Figure 6: Summary of the metric phrases

One approach to confirming the accuracy of the process is to re-transform the logical; statement back into prose (see figure 7). For clarity this representation uses names (in quotes) for the intermediate objective clauses to convey the strict logical expression that every object in the building must satisfy. In the constraint model these names are usually unique and arbitrary identifiers that are keyed into the text.

> *Compliance to "Dimensioning an access route to a building" is achieved by either not being an access route, or meeting "access route slope", "access route width", "access route landings" and "access route height". Compliance to "access route slope" is achieved by not being used by pedestrians and not being used by wheel chair users, or by not being steeper than 1:20 or by being a "short ramp". Compliance to "short ramp" is achieved by being shorter than 3 m and being less than 1:12.Compliance to "access route width" is achieved by having a clear width of 1.8 m , and having no obstacles, and by having a cross fall of less than 2%. Compliance to "access route landings" is achieved by having a horizontal landing at the start and end of the incline and by having a horizontal landing every 0.6 m of incline and by having a landing depth of 1.6 m. Compliance to "access route height" is achieved by having a clear height more than 2.25 m.*

Figure 7: A re-presentation of the derived logical statement as prose.

### 3.2 Test Case: A paragraph from the Dubai building regulation

In some cases normative documents include tabular inserts. This example (figure 8) shows how the tabular structure can be used along with the mark-up to infer the logical statement. This and the third example are concerned purely with the spatial structure of the building.

*Building Habitable Spaces*

*The minimum floor area and minimum dimension of any space in different types of building shall be as follows:*

| | *Minimum floor area* | *Minimum dimension* |
|---|---|---|
| ***Shop*** | *12.0 $m^2$* | *2.4 m* |
| ***Office*** | *10.0 $m^2$* | *2.5 m* |
| ***Residential room*** | *10.0 $m^2$* | *3.1 m* |
| ***Kitchen*** | *6.0 $m^2$* | *2.0 m* |
| ***Bathroom*** | *4.5 $m^2$* | *1.8 m* |
| ***Lavatory*** | *1.5 $m^2$* | *1.0 m* |

*It is permissible for some service rooms such as those used by servants and guard rooms to have a floor area of 6.5 m2 and a minimum dimension of 2.1 m.*

Figure 8: The regulation.

The original text including the table can be marked-up (figure 9). The confusion between building usage and space usage was raised with the building authority.

<R>***Building*** <a>***habitable spaces***</a>

*The minimum floor area and minimum dimension of any space in different types of building shall be as follow:*

| | *Minimum floor area* | *Minimum dimension* |
|---|---|---|
| <a>*Shop*</a> | <r>*12 $m^2$*</r> | <r>*2.4 m*</r> |
| <a>*Office*</a> | <r>*10 $m^2$*</r> | <r>*2.5m*</r> |
| <a>*Residential room*</a> | <r>*10 $m^2$*</r> | <r>*3.1 m*</r> |
| <a>*Kitchen*</a> | <r> *6 $m^2$*</r> | <r>*2.0 m*</r> |
| <a>*Bathroom*</a> | <r> *4.5 $m^2$*</r> | <r>*1.8 m*</r> |
| <a>*Lavatory*<a> | <r>*1.5 $m^2$*</r> | <r>*1.0m*</r> |

<E>*It is permissible for some* <a>*service rooms*</a> *such as those* <s>*used by servants*</s> *and* <s>*guard rooms*</s> *to have a* Stewart *floor area of 6.5 $m^2$*</r> *and a* <r>*minimum dimension of 2.1 m*</r> .</E></R>

Figure 9: The underlying mark-up tags

The mark-up of the table is similar to that applied to the prose text. The cells within the table typically contain applicability and requirement metrics. The table is read systematically and every interior cell with a requirement is made into a distinct test, taking any applicability from the upmost and leftmost cells.

| **Metric phrase** | **Type** | **Object** | **Property** | **Comparison** | **Target** | **Unit** |
|---|---|---|---|---|---|---|
| Shop (and others) | applicability | building/ space | usage | includes | Shop | |
| 12 $m^2$ (and others) | requirement | space | floor area | more than | 12.000 | $m^2$ |
| 2.4 m (and others) | requirement | space | short side | more than | 2.400 | m |

Figure 10: The underlying mark-up tags

The tabulation of the metric phrases (figure 10) shows that a small set of queries are needed to examine the building model.

*Compliance to "Building Habitable spaces" is achieved by either not being a habitable space or by meeting the "shop dimensions", "office dimensions", (…, or by meeting the "service exception". Compliance to "shop dimensions" is met by either not being a shop or by having area greater than 12 m$^2$ and short side greater than 2.4 m…). Compliance to the "service exception is made by being a service room, used by servants or a guard room or by having area greater than 6.5 m$^2$ and short side more than 2.1 m.*

Figure 11: The re-presention as prose (some test omitted for brevity).

The re-presented prose (figure 11) is correct but not particularly easy to read. A more sophisticated re-presentation transformation would be able to reconstruct the table.

### 3.3 Test case: US Court design guidance document

Guidance documents may not undergo the intensity of review and revision applied to regulatory documents. An example paragraph has been taken from the US Court Design Guidance (figure 12). It is not unusual to find undefined terms such as 'near' which may need to be negotiated and agreed between the client and the designer.

*The activities of the USDC focus on the courtroom. The courtroom requires direct access from public, restricted, and secure circulation. Ancillary spaces located near the district courtroom include: attorney/witness conference rooms accessed from public circulation; judge's conference robing room (provided only if the judges chambers are not located close to the courtroom) accessed from restricted circulation; trial jury suite accessed directly from the courtroom or restricted circulation; and prisoner holding cells accessed from secure circulation.*

Figure 12: The original guidance

In the original text, it may not be obvious that this is tabulating access requirements for specific spaces. The process of marking up isolates the separate requirements, along with some specific exceptions (figure 13).

*<R>**Major** <a>**Spaces**</a>*
*The activities of the USDC focus on the courtroom. <R>The <R>courtroom</a> requires <r>direct access from public</r>, <r>restricted</r>, and <r>secure circulation<r> </r></R></R><a>Ancillary spaces</a> located <r>near the district courtroom<r> include: <R><R><a>attorney/witness conference rooms</a> accessed from <r>public circulation</r></R>; <R><a>judge's conference robing room</a> <E>(provided only if the <a>judges chambers<a> are <r>not located close to the courtroom</r>)</E> accessed from <r>restricted circulation</r></R>; <R><a>trial jury suite</a> accessed directly from the <R><s>courtroom</s> or <s>restricted circulation</s></R></R>; and <R><a>prisoner holding cells</a> accessed from <r>secure circulation</r></R> .</R>.*

Figure 13: Guidance document with mark-up

The mark-up identifiers the ancillary spaces as being required to be near the courtroom and then details their individual access requirements. The requirements for access from the judges robing room are particularly subtle. The tabulation of the metric phrases (figure 14) shows that there are only three properties being used to assess the design. The interpretation of 'nearness' would need clarification, possibly supported by the use of 'fuzzy' logic and/or other forms of transformation.

| Metric phrase | Type | Object | Property | Comparison | Target |
|---|---|---|---|---|---|
| spaces | applicability | space | type | equals | TRUE |
| attorney/witness conference rooms | applicability | | | matches | attorney/witness conference rooms |
| courtroom | applicability | | | | courtroom |
| judges chambers | applicability | | | | judges chambers |
| judge's conference robing room | applicability | | | | judge's conference robing room |
| prisoner holding cells | applicability | | | | prisoner holding cells |
| trial jury suite | applicability | | | | trial jury suite |
| located close to the courtroom | requirement | | nearness | includes | courtroom |
| public circulation | requirement | | access | includes | public |
| restricted circulation | requirement | | | | restricted |
| secure circulation | requirement | | | | secure |

Figure 14: Summary of the metric phrases used in the guidance document

This re-presentation (figure 15) again uses names for the intermediate objective clauses to convey the strict logical expression that every space in the courtroom must satisfy. By systematic testing, a compliance checking engine can rapidly highlight any issues in the building and in the original document.

*Compliance to "Major spaces" is achieved by meeting the "courtroom access", and "ancillary access". Compliance to "Courtroom access" is achieved by either being not a courtroom or by having access to public circulation, having access to restricted circulation and having access to secure circulation. Compliance to "ancillary access" is achieved by either not being an ancillary space or by being near the courtroom and by meeting "ancillary space access". Compliance to "Ancillary space access" is achieved by meeting "attorney access", "judges robing access, "trial jury access" and "prisoner holding access". Compliance to "attorney access" is achieved by either not being an attorney/witness conference room or by having access to public circulation. Compliance to "judges robing access" is achieved by either not being a judges robing room or by having access to restricted circulation, or by meeting "alternative judges robing". Compliance to "alternative judges robing" is achieved by either not being a judges robing room or being close to the courtroom. Compliance to "trial jury access" is achieved by either not being a trial jury room or by meeting "alternative trial jury access". Compliance to "alternative trial jury access" is achieved by either being directly accessed from the courtroom or having access to the restricted circulation. Compliance to "prisoner holding access" is achieved by either not being a prisoner holding cell or by having access to secure circulation.*

Figure 15 : The re-presentation as prose

## 4 RESULTS / CONCLUSIONS

The expected result are is a quantitative determination of how valid and reliable the RASE methodology are on different categories of text. Whilst poorly written normative documents will naturally need extra care, the automatic generation of a logical statement appears robust with no clauses being un-handled, and the re-presentation accurately reflecting the original content. The use of mark-up to capture simple metadata give a foundation for both automatic and user-driven model checking systems.

The methodology also exposes the fundamental metric phrases which a building model server or user must answer during automatic or interactive model compliance checking.

The RASE technology give a significant improvement in reduced time and improved documentation for capturing requirements.

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**Paper 5**

# Experiences on converting interpretative regulations into computable rules

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# EXPERIENCES ON CONVERTING INTERPRETATIVE REGULATIONS INTO COMPUTABLE RULES

Eilif Hjelseth, Ph.D. student, eilif.hjelseth@umb.no
*The Norwegian University of Life Sciences (UMB), Dept. of Mathematical Sciences and Technology, Norway*

## ABSTRACT

The intention with this paper is to explore methods for increasing the number of regulatory statements that can be implemented into BIM-based model checking software in a valid and reliable way. The case is based on ISO 21542:2011 *Building construction -- Accessibility and usability of the built environment.* The methodology is based on classification of the structure of regulatory statements into three main categories: Transcribe, Transform and Transfer. The criteria for each category are founded on the capacity to respectively establish a direct, indirect or non-existing link between the qualitative goal/intention in the regulatory statement and the discrete quantitative metric required in computable rules. The challenge is to the increase implementation of statements classified as transformed. These types of statements are frequently used in performance based regulations. An ontology based method called “Test Indicator Objectives” is developed for bridging the gap between qualitative and quantitative expressions. Used methods identify a significant increase in number implementable rules. The results also indicate that interpretative statements, e.g. in performance based regulations, can be implemented in automatic or semi-automatic BIM-based model checking software. Used methods support large scale converting of regulations into computable rules.

**Keywords:** Model checking, regulations, ontology, knowledge representation, Building Information Modeling

## 1. INTRODUCTION

### 1.1 Importance of model checking for the AEC-industry

The AEC-industry is regulated by a great number of regulations, which are often updated. Use of BIM-based model checking software is increasing among professionals in the Architecture, Engineering and Construction industry (AEC-industry). Main focus has so far been mostly on clash-detection for assessment of model quality. Possibilities regarding compliance checking for verification of compliance, legality and building approval are announced as the next step for utilizing the potential of BIM. However, a limited number of regulations are implemented, and when done, it is often the simple prescriptive parts with simple logic and metric that is implemented. Qualitative performances based statements in regulations are generally omitted in implementation in BIM-based model checking software.

Public initiatives in handling of digital building applications and permissions are expected to have a critical impact on the AEC industry. Examples of solution in practical use are the CORENET e-Submission System in Singapore (CORENET, 2012), Byggsøk in Norway (ByggSøk, 2012), and the Planning Portal in England and

Wales (Planning Portal, 2012). Commercial software like Solibri Model Checker (Solibri, 2012), in addition to BIM- / IFC-based model servers (BIMserver, 2012), enables practical checking and review of digital models. So far has most focus been on clash detection of digital models with limited information. Increased information in the BIM content and in the rule-sets of regulations will enable support for compliance checking of selected parts of certification systems like LEED; Leadership in Energy and Environmental Design (LEED, 2011) or BREEAM; Building Research Establishment Environmental Assessment Method for buildings (BREEAM, 2012).

### 1.1 Performance versus prescriptive based model checking

The two main concepts for regulatory systems are the performance and the prescriptive based system. Both types of regulatory statements can be used within one regulation document; law, code, act, standard, public guideline, directive etc.

Performance based specifications are known as "recipe" specifications, while prescriptive specifications are known as "end result" specifications (Gibson, 1982). BIM-based model checking software works with discrete metric. Prescriptive statements are therefore in principle prepared for implementation into BIM-based model checking software.

Performance based specifications have quantitative goals or objectives. They are in principle much more interpretable, but might give better conditions for innovative new solutions (Oleszkiewicz, 1994). Implementing this type of statements into model checking software is not a straight forward process. Organizations like IRCC, Inter-jurisdictional Regulatory Collaboration Committee, (2012) work purposefully for increased development and implementation of performance based regulations in its 19 member bodies. These countries are; Australia, Austria, Canada, China, Japan, New Zealand, Norway, Scotland, Singapore, Spain, Sweden and the USA.

### 1.2 Research in this domain

Model checking in the AEC industry is gaining increased interest due to use of BIM-based design software. The research domain is not clearly defined and range from technical issues and capacities in data schemas (IFC) to semantic (IFD) and logical challenges of understanding of language and presentation of rules. Other approaches projecting on the legal issues regarding performance based versus prescriptive regulations. Georgia Tech University in USA has published a number of papers, mostly with a technical approach focusing on IFC capacity. CSTB (Centre Scientifique et Technique du Bâtiment) in France is active and focus on systems for large based on database queries (SPARQL). In the Netherlands focus has been on ontology and model server and should be regarded as part of or support to this domain of research. In Belgium is Smartlab project at Ghent University working active on rule checking research. CRC Construction Innovation in Australia has developed software solutions based on JESS as rule engine, in addition to publication of scientific papers. Korea is active in BIM research and at the Kyung-Hee University research is done in compliance checking. However, the AEC related research communities are generally small without any dominating institution or research program.

### 1.3 Research questions and objectives

This paper is an extension and maturing of concept based papers presented at CIB W78 and ECPPM conferences by Hjelseth (2009, 2012) and Hjelseth & Nisbet (2010a, 2010b, 2011). The results in this paper are based on a case study of the complete version of the "ISO 21542:2011 *Building construction -- Accessibility and usability of the built environment*" standard. The standard has a volume of 152 pages; 42 clauses and 5 annexes.

The research questions focus on practical experiences with following two methods:

- "Tx3" as a methodology (further explained in chapter 2) for increased control of development computable rules from regulations. Starting with a classification of regulations into three types of rules; Transcribe, Transform and Transfer, gives a numeric overview of how much of the regulation can be implemented as computable rules. The methodology follows a pre-defined procedure where each step is transparent and identifiable. The objectives will be increased control of time/cost and methodology (including supporting systems) in an early phase of development of rules. The case study will have main focus on identifying the “Transform” type of regulatory statements. These regulations are candidates for the TIO-methodology.

- “TIO”, Test Indicator Objectives, as a methodology (further explained in chapter 3) for increasing his paper focus on converting performance based regulations by use of a mapping methodology named TIO. TIO provides a transparent mapping between the qualitative goal/intention in regulations and the corresponding quantitative, discrete, metric in the computable rule. The TIO-methodology will be used to try to increase the number of rules that can be interpreted in BIM-based software.

## 2. USE OF THE $T_X$3-METHODOLOGY FOR CLASSIFIATION OF REGULATORY STATEMENTS

The Tx3-methodology includes three procedures; Transcribe, Transform and Transfer (Hjelseth, 2012). Please note that statements classified as “Transcribe” in previous papers has been named “Translate”.

The Tx3-methodology is structured into specified levels (tiers) illustrated in figure 1. This paper focuses on transforming regulatory statements by support of the TIO-methodology, explained in chapter 3. This methodology is applied in the “#2-A, Association rule” process, marked with the doted circle in figure 1.

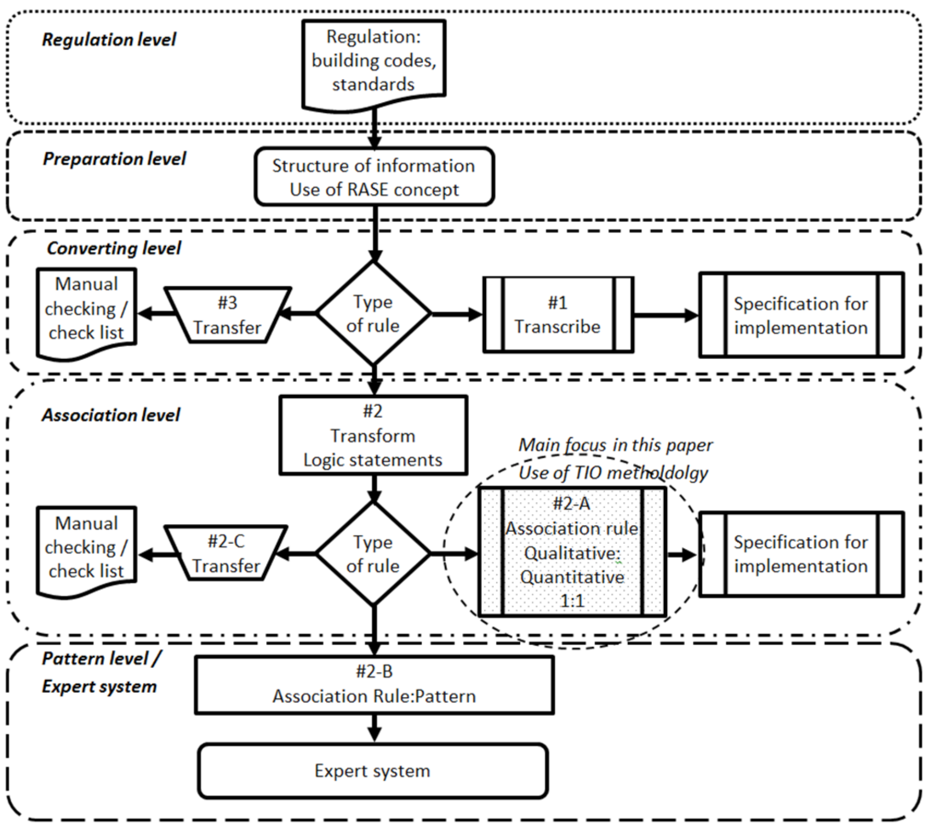


Figure 1: Flow chart of the Tx3-methodology for converting of regulations into computable rules.

*Regulation level:*
"Regulation" is used as a common term in this paper for all types of laws, building codes, acts, directives and standards. This paper does not focus on the hierarchy of legislation.

*Preparation level*
Regulations are written in a legal / technical language and must often be re-structured before they can be used as specifications for implementation in software. Preparation from free text to normative structure in tables can e.g. be done by use of the RASE-methodology. This is a semantic based mark-up methodology using the following four RASE operators: 'Requirement' 'Applies, 'Select', and 'Exception'. Practical use of this methodology is explained in paper by Hjelseth and Nisbet (2011), accessible from CIB-W78 2011 conference site. Applied on a normative regulatory text, the user highlights any clause or phrase that means: • 'shall'/'must' as a 'Requirement', • less scope as an 'Applies', • more scope as a 'Select', • 'unless' as an 'Exception'.

*Converting level*
The converting level classifies regulatory statements based on a simple taxonomy for identifying the target criteria of validation. This concept is named "Tx3-methodology" and is based on classification into three main categories: Transcribe, Transform and Transfer. The criteria for each category are founded on the capacity to respectively establish a direct, indirect or non-existing link between indicator qualitative or quantitative intention in the regulatory statement and a discrete quantitative metric applicable in rules. The taxonomy of type of rules is illustrated in figure 2.

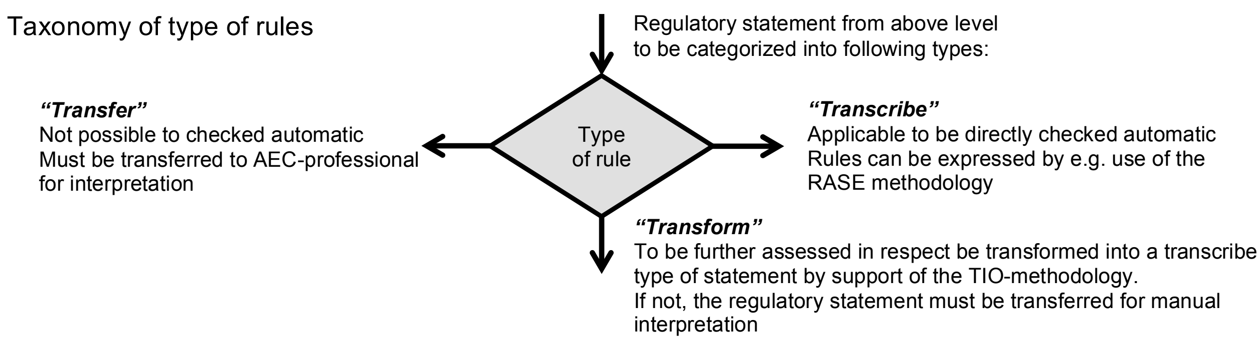


Figure 2: Taxonomy of type of rules

Regulatory statements classified as "Transcribe" can be expressed as computable rule by pre-defined procedures like e.g. RASE. The challenging part is statements classified as "Transform". Whether these statements can be expressed as (transformed to) to computable rule is decided on the "Association level". "Transfer" to skilled AEC-professionals for interpretation will often be the best solution for regulatory statements that are very dependent on its context, large number of constraints and information in the model.

*Association level*
The association level is in this study supported by the TIO-methodology, "Test Indicator Objectives", which is further explained in next chapter. TIO can be regarded as an "association rule" which in a transparent, valid (includes context dependency) and reliable way establishes a mapping between the qualitative goal/intention in the regulatory statement and the discrete quantitative metric required in computable rules.

*Pattern level / expert system*
Pattern level / expert system is an option to solve more complicated regulatory statements by support of methods and technology based on KBE (Knowledge Based Engineering), AI (artificial intelligence) and expert systems is necessary. However, the most common solution is to let a skilled AEC-professional interpret these regulatory statements manually.

## 3. TIO – TEST INDICATOR OBJECTIVES

### 3.1 Consensus about criteria for verifications

The main principle challenge is to obtain consensus between qualitative statement in regulations and quantitative metric applicable in rules. This transformation into practical criteria in BIM-based model checking software must be done without "messing up" area of application in the regulatory source. Qualitative and quantitative expressions are in principle incomparable. However, from an AEC-professional perspective, there is often consensus about practical solutions / consequences, even if they are formulated as qualitative statements. Terms (language) within AEC-industry are limited domain, and according to Sowa (2000) should a shared understanding be achievable. Ontology can be regarded as a concept for shared understanding, which focus on "what it is", and not only "what it is called". According to Gruber (1995) is ontology defined as formal specification of a shared conceptualization. Use of engineering ontology has been presented by Beetz et al. (2008) as a way of transforming understanding. A shared understanding should therefore be possible to achieve regarding transforming of regulations into computable rules.

### 3.2 Association between qualitative objects and quantitative metric

The challenge is to develop a valid and reliable way to interpret regulatory statements that enables an implementation into model checking software in a transparent, valid and reliable way. Transformable rules are characterized by an indirect relation between the qualitative objectives (goals/intentions) in the regulation and discrete quantitative metric in the rules applicable for implementation into BIM-based model checking software (Hjelseth, 2012). Examples of practical use are presented in table 1. "Test Indicator Objectives" (TIO) is a methodology that provides a transparent mapping between the qualitative goal in regulations and the corresponding quantitative, discrete, metric in the computable rule. The TIO-methodology is illustrated in figure 3 and can be done by "Top-down" and /or "Bottom-up" approach. The end result will be expressed as a single metric with a discrete value. Use of alternative values in the rule-sets can enable parametric model checking. The TIO-methodology is more detailed described in a previous paper by Hjelseth (2012). TIO is an attempt to use a simple methodology as possible for increasing number of computable rules.

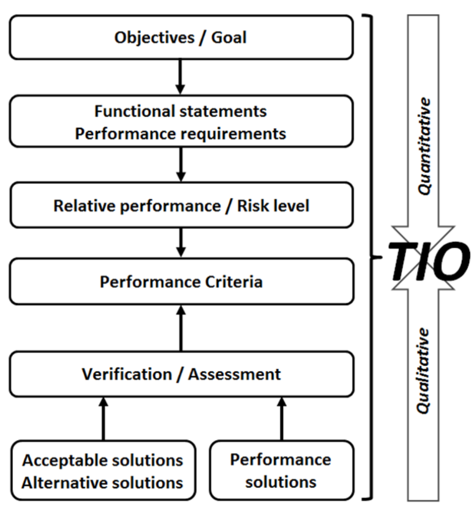


Figure 3: Relation between qualitative and quantitative regulations – scope of TIO (Hjelseth, 2012).

### 3.3 Example of TIO's based on ISO 21542:2011 standard

Exploring the ISO 21542:2011 standard resulted in 90 "shall rules", (23% of shall rules) and 89 "should rules" (30% of should rules) classified as "Transform" type of rules, representing 26% of total type of rules. For enabling automatic model checking must these types of rules with qualitative objectives be transferred into discrete metric. This will have a significant impact on the efficiency. It is important to be aware of that when the logical rule is established; these requirements can be regarded as parametric instances. This approach can enable performance checking at different levels; one rule-set with the minimum requirements, and another with higher requirements. Table 1 present a TIO-dictionary where qualitative goals are transformed into qualitative metrics.

Table 1: TIO-dictionary for transformed qualitative goals into qualitative metric

| **Clause** | **Shall/ Should** | **Qualitative expression of goal** ***text of statement in ISO standard*** | **Test Indicator Objectives (TIO)** | **Quantitative metric** =, <, > |
|---|---|---|---|---|
| ***Minimum dimension*** | | | | |
| 7.6 | Shall | ..powered wheelchair.. *If larger powered wheelchairs and scooters for outdoor use are to be considered, the outer radius of a turning space should be larger.* | Dimension of powered wheel-char, different types, in mm | *x* mm |
| 26.3 | Should | ..visually contrast… *Fixtures and fittings in sanitary facilities should visually contrast with the items and surface on which they are positioned* | Use of LRV | *x* LVR |
| 40.8 | Should | ..well illuminated… *Signs should be well illuminated with no glare* | Minimum illumination in lux | *x* lux |
| ***Maximum dimension*** | | | | |
| 6.8.3 | Should | ..as close as possible... *Location of accessible parking spaces (indoor parking) should be as close as possible to the entrances/lifts.* | Maximum distance in mm | *x* mm |
| 18.1.9 | Shall | sufficient time… *A powered swing door shall be fitted with a return delay mechanism that allows sufficient time for safe passage and for detecting the presence of a person lying on the floor within the door closing area.* | Maximum time in seconds | *x* sec. |
| ***Pre-accept solution*** | | | | |
| 18.3.2 | Should | ..easy to use; open and close.. *Windows should be easy to open and close. It should be possible to open and close the windows with only one hand.* | Pre-accepted (approved) type of window | Approved by *x* organization |
| 26.5 | Shall | ..easy to open and close.. *The door shall have an unobstructed width of at least 800 mm, with minimum 850 mm as a recommended value, and it shall be easy to open and close. The door should open outwards.* | Pre-accepted (approved) type of window | Approved by *x* organization |
| ***Product property – Surface*** | | | | |
| 6.7 | Shall | Kerbs...slip-resistance.. *Kerbs shall have a slip-resistance surface.* | Specify friction coefficient on kerbs | 0.*x* |
| 25. | Shall | Walking surfaces…slip-resistant.. *Walking surfaces shall be slip resistant.* | Specify friction coefficient for walking on terraces, verandas and balconies | 0.*x* |
| 26.3 | Shall | Floor surface…shall be slip resistant.. *The floor surface shall be slip resistant, anti-glare and firm.* | Specify friction coefficient for floors | 0.*x* |
| 31 | Shall | Floor coverings…slip-resistant in both dry and wet conditions.. *Floor coverings shall be firm and slip-resistant in both dry and wet conditions.* | Specify friction coefficient for floor coverings | 0.*x* |

## 4. RESULTS FROM THE FEASABILITY STUDY OF ISO 21542:2011 STANDARD

### 4.1 Classification of statements in ISO 21542:2011 standard into Tx3 types of rules

Table 2 is representing an overview of how the 680 statement are categorized into the three types of rules: transcribe, transform or transfer. *) Clause references include sub and sub-sub clauses. For documentation and identification have all rules a direct reference to the origin statement in the ISO 21542:2011 standard document.

Table 2: Tx3 classification of type of rules in the ISO 21542:2011 standard.

| **Clause in ISO 21542:2011 *)** (Clause 1 to 4 are general parts) | **Shall rules** | | | | **Should rules** | | | | **Total number of rules** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **T1** | **T2** | **T3** | **∑T** | **t1** | **t2** | **t3** | **∑t** | **T1 +t1** | **T2 +t2** | **T3 +t3** | **∑T +t** |
| 5.Approach to the building | 2 | 1 | 0 | 3 | 0 | 0 | 0 | 0 | 2 | 1 | 0 | 3 |
| 6.Designated accessible parking space | 14 | 5 | 3 | 22 | 5 | 3 | 0 | 8 | 19 | 8 | 3 | 30 |
| 7.Paths to the building | 34 | 5 | 3 | 42 | 3 | 1 | 6 | 10 | 37 | 6 | 9 | 52 |
| 8.Ramps | 11 | 2 | 0 | 13 | 3 | 1 | 0 | 4 | 14 | 3 | 0 | 17 |
| 9.Guarding along paths and ramps | 3 | 0 | 1 | 4 | 0 | 0 | 0 | 0 | 3 | 0 | 1 | 4 |
| 10.Building entrances and final fire exits | 11 | 2 | 2 | 15 | 1 | 3 | 3 | 7 | 12 | 5 | 5 | 22 |
| 11.Horizontal circulation | 15 | 3 | 1 | 19 | 2 | 0 | 1 | 3 | 17 | 3 | 2 | 22 |
| 12.Vertical circulation | 1 | 0 | 0 | 1 | 0 | 1 | 2 | 3 | 1 | 1 | 2 | 4 |
| 13.Stairs | 14 | 2 | 0 | 16 | 6 | 3 | 0 | 9 | 20 | 5 | 0 | 25 |
| 14.Handrails | 9 | 0 | 2 | 11 | 1 | 0 | 0 | 1 | 10 | 0 | 2 | 12 |
| 15.Lifts (Elevators) | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| 16.Vertical and inclined lifting platforms | 1 | 0 | 3 | 4 | 0 | 0 | 0 | 0 | 1 | 0 | 3 | 4 |
| 17.Escalators and moving walks | 2 | 1 | 1 | 4 | 0 | 1 | 2 | 3 | 2 | 2 | 3 | 7 |
| 18.Doors and windows | 18 | 4 | 4 | 26 | 7 | 4 | 7 | 18 | 25 | 8 | 11 | 44 |
| 19.Reception areas, counters, desks… | 8 | 1 | 2 | 11 | 0 | 3 | 2 | 5 | 8 | 4 | 4 | 16 |
| 20.Cloackroom | 1 | 0 | 0 | 1 | 2 | 0 | 0 | 2 | 3 | 0 | 0 | 3 |
| 21.Auditoriums, concert / sports seating | 4 | 0 | 1 | 5 | 9 | 4 | 2 | 15 | 13 | 4 | 3 | 20 |
| 22.Conference rooms and meeting rooms | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 2 |
| 23.Viewing spaces in assembly areas | 1 | 2 | 3 | 6 | 0 | 2 | 0 | 2 | 1 | 4 | 3 | 8 |
| 24.Bars, pubs, restaurants, etc | 0 | 0 | 4 | 4 | 0 | 0 | 1 | 1 | 0 | 0 | 5 | 5 |
| 25.Terraces, verandas and balconies | 0 | 1 | 1 | 2 | 0 | 0 | 1 | 1 | 0 | 1 | 2 | 3 |
| 26.Toilet rooms and sanitary rooms | 54 | 39 | 3 | 96 | 30 | 12 | 4 | 46 | 84 | 51 | 7 | 142 |
| 27.Access. bedrooms in non-dom. build.. | 6 | 1 | 1 | 8 | 2 | 0 | 0 | 2 | 8 | 1 | 1 | 10 |
| 28.Kitchen areas | 0 | 1 | 1 | 2 | 0 | 2 | 1 | 3 | 0 | 3 | 2 | 5 |
| 29.Storage areas | 1 | 1 | 0 | 2 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 2 |
| 30.Facilities for guide-/ assistance dogs | 0 | 0 | 0 | 0 | 2 | 1 | 2 | 5 | 2 | 1 | 2 | 5 |
| 31.Floor and wall surfaces | 0 | 1 | 0 | 1 | 0 | 2 | 1 | 3 | 0 | 3 | 1 | 4 |
| 32.Acoustic environment | 1 | 0 | 0 | 1 | 1 | 0 | 2 | 3 | 2 | 0 | 2 | 4 |
| 33.Lighting | 6 | 5 | 0 | 11 | 1 | 10 | 3 | 14 | 7 | 15 | 3 | 25 |
| 34.Fire emerg. warning syst., signals/info | 0 | 1 | 1 | 2 | 0 | 5 | 2 | 7 | 0 | 6 | 3 | 9 |
| 35.Visual contrast | 5 | 2 | 0 | 7 | 2 | 0 | 0 | 2 | 7 | 2 | 0 | 9 |
| 36.Equipment, controls and switches | 14 | 4 | 2 | 20 | 32 | 15 | 5 | 52 | 46 | 19 | 7 | 72 |
| 37.Furnishing | 2 | 0 | 0 | 2 | 8 | 0 | 2 | 10 | 10 | 0 | 2 | 12 |
| 38.Fire safety, protect. and evacuation… | 0 | 1 | 2 | 3 | 0 | 1 | 7 | 8 | 0 | 2 | 9 | 11 |
| 39.Orientation and information | 0 | 0 | 2 | 2 | 0 | 3 | 5 | 8 | 0 | 3 | 7 | 10 |
| 40.Signage | 14 | 2 | 0 | 16 | 9 | 11 | 12 | 32 | 23 | 13 | 12 | 48 |
| 41.Graphical symbols | 3 | 3 | 0 | 6 | 1 | 0 | 1 | 2 | 4 | 3 | 1 | 8 |
| 42.Management and maintenance issues | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 |
| **Number of rules** | 256 | 90 | 43 | **389** | 127 | 88 | 76 | **291** | 383 | 178 | 119 | **680** |
| **Percent of Shall/Should rules** | **66%** | **23%** | **11%** | **100%** | **44%** | **30%** | **26%** | **100%** | | | | |
| **Percent of rules total** | 38% | 13% | 6% | | 19% | 13% | 11% | | **57%** | **26%** | **17%** | |
| **Accumulated percent of rules** | 38% | 13% | 6% | **57%** | 19% | 13% | 11% | **43** | 57% | 26% | 17% | **100%** |

The Tx3-methodology and criteria for categorization are explained in chapter 3. The study is based on all normative clauses in ISO 21542:2011 standard except Clause 15 “Lifts (Elevators)”. In this study was this clause is regarded as requirement to a specified type of object defined as lifts (elevator) which have to be “approved” in compliance with ISO 21542:2011 and related standards. Excluding this clause is therefore considered have no consequences on the validity of this study.

This case study indicates that the applicability of regulatory statements for implementation into BIM-based model checking systems can be identified by the Tx3-methodology for classification. This can be used as a foundation for predictable development process of specifications of computable rules implementable in BIM-based software.

The normative statements in complete ISO 21542:2011 standard was classified into 680 rules (389 shall and 291 should). 57% percent of rules were classified to be “transcribe” type, which is direct into applicable rules for automatic BIM-based model checking software (The “production” of rules could e.g. be done by the semantic based RASE-methodology for structuring of statements into computable rules). Of the remaining 43% of rules - 26% was classified as transformed and applicable for the TIO-methodology, while 17% of the rules had a structure which was not applicable for transforming by TIO. Support of more advanced / context related techniques / expert systems and more advanced techniques can be an alternative to manual interpretations (Hjelseth 2012).

### 4.2 Distribution of Tx3 type of rules

Figure 4 illustrates the percentage distribution of rules classified by the Tx3-metholdology (see chapter 3 for information about the methodology). The rules are presented as “Shall” and “Should” level of regulation, in addition to an accumulated diagram. Please note that the area of the diagram is adjusted to number of rules.

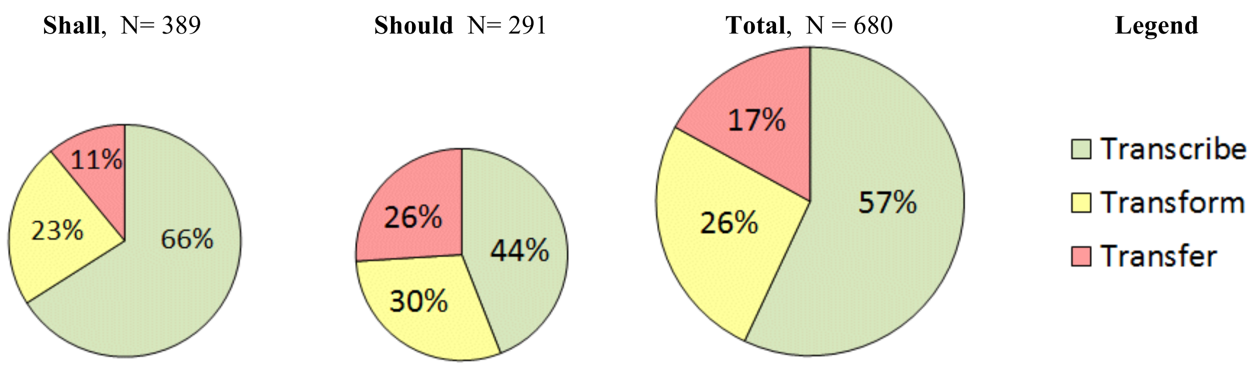


Figure 4: Overview of type of rules in the ISO 21543:2011 standard

### 4.3 Use of TIO-method to increase degree of automatic model checking of ISO 21542:2011 rules

Figure 5 illustrates the effect of the “Test Indicator Objectives” (TIO) as a methodology for transforming (mapping) qualitative goals in the regulations into discrete metric for enabling automatic model checking.

The results of this case study confirmed that it was possible to transform the identified 26% or “transform” type of rules by use of the TIO-methodology. The TIO transformation can be presented as a mapping table, see table 1. The impact for verification of accessibility is that the amount of rules which have to be checked manually is reduced from 43 % to 17% of total number of rules.

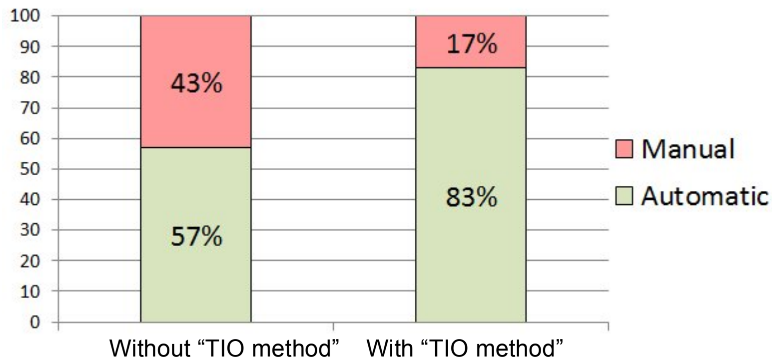


Figure 5: Effects by the TIO-methodology on model checking

## 5. DISCUSSION

The results are based on use of the Tx3-methodology for classification and the TIO-methodology for transforming statements applied one single regulation, the ISO 21542:2011 standard. The validity of using these methods is supported by previous papers by Hjelseth (2009, 2012) and Hjelseth & Nisbet (2010a, 2010b, 2011). Both Tx3 classification of statements and development of TIO metrics is a manual process and the precision of classification into the three types can therefore be debatable. The Tx3 classification of "transcribe" type of rules (57%) will due to direct relation be fairly unambiguous. Classification into "transform" (26 %) and "transfer" (17 %) type of rules is related to choose of method for transforming or interpreting qualitative goals into quantitative metrics. This study is founded on use of the TIO-methodology. It can be expected that some statement classified as "transform" become too difficult to obtain consensus about transformed metric and TIO must be transferred to manually interpretation. On the other hand can regulatory statements classified as "transfer" be able to be transformed in a way that is applicable for automatic model checking by support or more advanced methods than TIO, or by including constraints, context awareness and limitation in complexity for when it can be used.

## 6. CONCLUSION

The ISO 21542:2011 standard for accessibility was used as a case to explore the applicability of two methods:
- Tx3-methodology for classification of types of rules and how they can be implemented
- TIO-methodology, Test Indicator Objectives; for transforming qualitative goals in the regulations into quantitative metric in the computable rule

This case study indicates that the suitability of regulatory statements for implementation into BIM-based model checking systems can be identified by the Tx3-methodology for classification. The impact of this a predictable development processes that identify which statements that can be verified automatic in BIM-based software, and which regulatory statement that still must be interpreted manually.

Experiences with the TIO-methodology were that it enables a transparent, valid and reliable way to increase the number of regulatory statements that can be implemented into BIM-based model checking software. This effect is especially relevant for performance based regulations. The study indicated an increase in from 57% to 83% in amount of rules which can be verified automatic. Viewed in reduction of manually interpretations is this representing about a halving, from 43 % to 17% of total number of rules that must be verified manually.

The general experiences from this study support a shift of approach from an open development process towards use of predictable production procedures in specification of computable rules. The results can also be regarded as an indication that performance based regulation can be used as reliable bases for automatic / semi-automatic BIM-based model checking.

## 7. FURTHER RESEARCH

Further research will focus on whether required information specified in the rules is in compliance with the entities and property sets (Psets) in the IFC 2x3 and 2x4 data schema. The research methodology will be based on development of IDMs and BIM-guidelines. The author appreciates feed-back from corresponding projects.

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**Paper 6**

# BIM-based model checking (BMC)

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# CHAPTER 2

# BIM-based Model Checking (BMC)

Eilif Hjelseth*

**Abstract:** *This chapter presents Building Information Model (BIM)-based model checking (BMC). BMC is often referred to as one of the major benefits in utilizing BIM, where everyone can perform compliance checking and design coordinating. Wide use of BMC software in BIM-based projects should therefore be expected. This study is based on a broad approach, ranging from exploring principles of model checking to practices in state-of-the-art companies, in addition to reviewing commercial software. Outcomes indicate that functionality in commercial software covers requirements for model checking in projects based on the use of simple rules and unspecified content of information in the BIM-file. Improved collaboration based on coordinating merged BIM-files and automatic clash detection was regarded as the main benefit. BMC was regarded as a part of company quality assurance systems for model coordination. Wide use was not observed, and the use of BMC software was regarded as a specialist tool operated by a limited number of users. This study indicates a potential for the further development of rule sets and procedures for trustworthy compliance checking. In this respect, BMC can be regarded as a catalyst for the exchange of high-quality BIM for cross-disciplinary collaboration. Utilization of BMC can be an indicator of BIM-maturity.*

## INTRODUCTION

### BIM-based Model Checking (BMC)

BMC is the process which processes the content of information in BIM-files according to rules specified as pre-defined procedures. The components in BMC consist of three components: software, rule sets, and BIM-files. This division into the components enables to focus and improve each of the components – and the

*Department of Mathematical Sciences and Technology, Norwegian University of Life Sciences (NMBU), P.O. Box 5003. NO-1432 Aas, Norway; Phone (+47) 64 96 54 00; Fax (+47) 64 96 54 01; email: eilif.hjelseth@nmbu.no

relation between the components. BMC is therefore not only solved by buying software and hit the 'checking' button.

BMC is perhaps one of the best ways to illustrate the power of relevant information in BIM-files. Model checking explores the content of information in BIM-files in a transparent way. Statements like improving the BIM by enriching the model and increasing the amount of information are not valuable unless the information is relevant for the information required to process the rule. The rule must also be relevant for what one intend to check. The development of new rules, or adaptation of existing rules, is often required.

This aspect can also be used to illustrate the distinction between BM (Building Model/3-D model) and BIM with a focus on the '*I in BIM*', where I stand for information. The BIM community is in its expansive phase, and proponents are claiming that BIM in general, and model checking in particular, will be a game changer. The approach in this chapter tries to be more balanced. The opportunities are great, but this requires a high degree of input of relevant information from BIM-files and advanced, precise rules for processing. The maturity level in exchanging BIM-files with a highly specific content of information is currently low.

### Structure of This Chapter

This chapter has a broad scope and is structured into several parts. The first part provides examples of BMC. The importance of BMC is documented with reference to several studies. This part also intends to give the use of BMC a position as something more than being skilled in use of software. Organizational aspects must be taken into account. The second part introduces principles and classification in the use of BMC. The close relation to BIM is included in this part. The third part gives an overview of commercial BMC software. BMC has a number of aspects, and the final part explores what can be checked – and what cannot be checked. This part focuses on the important development of rule sets for enabling advanced model checking. It includes a study of state-of-the-art companies in Norway as well as their experiences and suggests future development.

## EXAMPLES OF BMC

### Clash Detection

Use of BMC, or model checking, is often used synonymously with clash detection. Clash detection is a useful way to demonstrate the benefits of BIM in model checking software, such as Navisworks from Autodesk or Solibri Model Checker from Solibri. Clash detection in the BIM is one of the most common ways to demonstrate the practical uses of BMC. BMC replaces or supports the traditional quality assessment of drawings. Quality assurance (QA) is a key aspect in BMC. Figure 2-1 shows an example of a conflict between a structural beam and a ventilation duct.

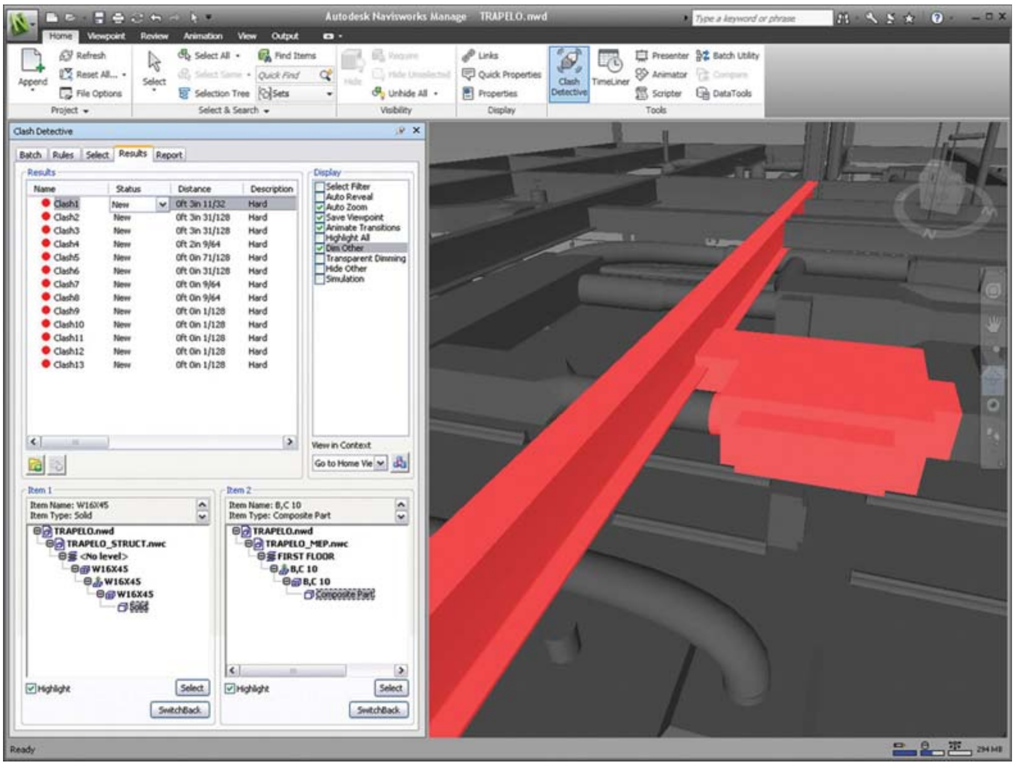

*Figure 2-1. Clash detection by use of Navisworks software (Courtesy: Navisworks 2013).*

This important issue would probably have been detected by visual checking. The benefit from BMC is often more significant if the issues are many, small, and hard to visually identify. BMC testing gives identical results every time it is processed and has a higher reliability (quality) than visual inspection.

One practical problem of automatic clash detection is that it can provide too many false issues. The QA responsible must then spend time sorting relevant issues from non-relevant issues. BMC software has features to handle this in an efficient way. The background for this over-reporting is the attitude that it is better to report ten times too many issues than miss one issue. The technical background is that the rules for clash detection are coarse, and the precision of information in BIM files is not specific enough.

However, BMC can be used in a large number of tasks. The 'BMC = clash detection level' can be more like a plateau – a comfortable level to stay within without seeking solutions above that level. BMC has an unrealized potential for solving new types of problems in new ways. This future-based aspect is covered later in this Chapter.

## *Smart BMC*

The general challenge for BMC, and particularly clash detection, is massive reporting of non-real issues – which has to be dismissed manually. Model-checking

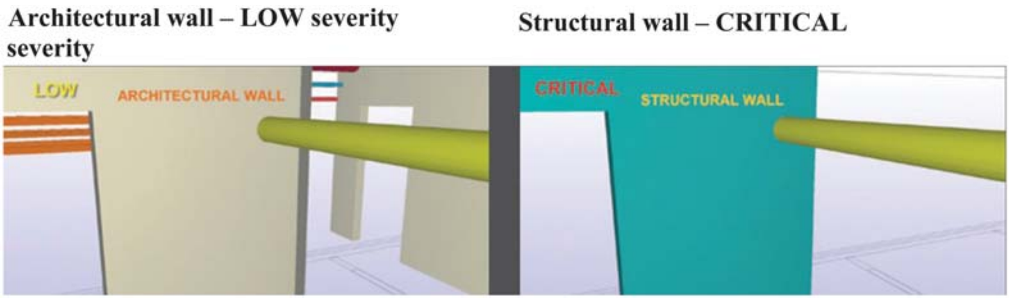


*Figure 2-2. Rule-based reasoning used to assess impact of rule violation, case: wall-pipes interference (Courtesy: Solibri 2010).*

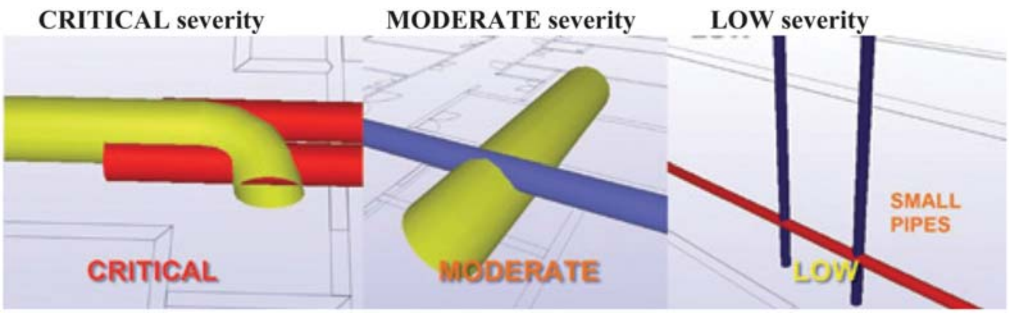


*Figure 2-3. Rule-based reasoning used to assess the impact of rule violation, case: pipes of different diameter (Courtesy: Solibri 2010).*

software has a function for marking the issues as not relevant. Severities of issues are often graded by degree of deviation from the rule constraints, not from technical or economic impact. The information in the BIM file enables BMC software to grade the issues by other criteria, like the type of wall. Figure 2-2 illustrates reasoning to assess the impact of rule violation. Interception of a structural wall may be critical while an architectural wall may be cut without severe impact. In a proper object model, the wall type will be derived from the class of the wall object.

Figure 2-3 shows examples of 'Critical', 'Moderate' and 'Low' severity issues. Interference between small pipes is considered low severity since that is possible to fix on site. Rule-based reasoning contributes significantly in addressing the most relevant issues first and when required. However, it is not always obvious that small pipes are easy to move. An example is pneumatic dispatches in hospitals, for which bends are to be avoided. Rule-based reasoning can improve model checking.

## BMC Software as Coordination and Reporting Tools

Coordination of models from different disciplines in the design and construction process is an important feature of BMC. BMC software such as Navisworks and Solibri have features for merging BIM-files into a single common coordinated model. Reports can be exported in PDF, XLS, or BCF format. The BIM collaboration format (BMC) introduces a workflow communication capability connected to IFC models. The idea is to separate communication from the actual model. The BCF format is based on XML (Stangeland 2011).

## ADOPTION OF BMC IN THE CONSTRUCTION INDUSTRY

### High Expectations in the Construction Industry

Eastman stated in the status report from McGraw-Hill Construction (2012) that model checking is the most important current BIM requirement to effectively advance the industry, followed by improved interoperability. Increased model quality with correct solutions is a great motivation for using BMC. Another rationale for model checking is to provide models free of issues so that data can be trusted when used in other software and processes.

A study from the AutoCodes project (Fiatech 2012) in the International Code Council (ICC) illustrates that manual checking gave uncertain answers. The number of issues flagged by various jurisdictions differed widely. When one jurisdiction raised one single issue, another raised 43 issues. A lesson from this study is that what is manually checked or not checked is actually undefined. Sawyer (2012) expressed that analysts only know what they found in a manual Q1 review, but did not really know what they actually looked at in the review. BMC processes pre-defined rules, so the scope of review is determined by the selected rule set. One consequence is that a situation which lacks rules will not be checked. Knowing the scope of all rules in a rule set is important for a trustworthy review. A survey of 139 projects indicates that design issues increased direct costs by 6.9% and indirect costs by 7.4% of the total contract value (Lopez and Love 2012). A study by Conover (2007) showed that on average, 3% to 5% of the design time of a construction project is currently devoted to code-checking, and even then, not everything is checked.

Status reports from McGraw-Hill Construction (2012) point out more clearly defined BIM deliverables between parties as one of the five top-rated areas for improvement. High-quality BMC can be a deliverable. A more pervasive benefit of BMC is presented in a video from the AutoCode project by Fiatech (2013). This video illustrates that time spent on code checking can be reduced from months to minutes. ICC board president Ronald Piester says that automated code checking helps reviewers focus on the core tasks of code compliance and speeds up the permitting process. Piester says that this innovative technology will provide comprehensive and consistent results from project to project across jurisdictions and allow code officials to dedicate more time to safety issues, inspections, and other important duties (Fiatech 2012). Architects on average spend almost 50 hours per project on code checking, and 11% spend more than 100 hours. Approximately 85% of architects are positive about working with model checking software to support the code checking process (McGraw-Hill Construction 2007).

### Public Services and BMC

Building authorities look at BMC as a concept for the automatic processing of applications. This type of validation requires transforming regulations into computable rules for processing building permit applications. So far, only a limited number of projects have been completed, but this is expected to change significantly in the near future. An international state-of-the-art survey by Refvik (2013) identified projects in Korea, Japan, and further development of existing solutions in Singapore, the UK, and Norway. BMC was reported to be included in future solutions but was currently not a part of the verification of applications. The existing solutions were based on verification of application forms filled in manually. This chapter does not focus on software solutions for public purposes since most countries will develop their own software solution for processing based on national requirements. These types of software solutions will also include a large number of administrative services in addition to compliance checking based on input from BIM-files and other sources. Use of commercial software will therefore not be relevant for these types of solutions. BMC was intended to be solved by use of model server technology.

According to Shih et al. (2013), public authority provides a foundation for the development of code-checking systems using BIM to assess compliance with building codes. Not only do code checking systems have the potential to enhance designers' awareness of building codes, but they also have the potential to improve collaboration and communication among project stakeholders.

## PRINCIPLES OF BIM-BASED MODEL CHECKING (BMC)

### The Components of BMC Systems

A BMC system consists of three parts: software, BIM files, and rule sets. Figure 2-4 illustrates the integrated relationship between logic in a rule set, the content of information in a BIM file and functions in model checking software.

- Software includes the service and function enabling import of BIM files, processing of rules, visualization and reporting of issues. An overview of software is presented later in this chapter.
- The quality of the BIM file, measured as the structure and content of relevant information, is of high importance for reliable model checking. This must comply with requirements in the rule to avoid the 'garbage in-garbage out' syndrome. BIM guidance and similar specification of content in the BIM file can be used to address the specification of information.
- Rule sets are collections of rules within one topic, such as BIM validation (clash detection), space validation, identifying updates between different versions of the design, comparing the structural versus architectural model, MEP solutions, and content in BIM file (Statsbygg BIM guidance). Today, the rule-set is a part of the commercial software package. It is often possible to

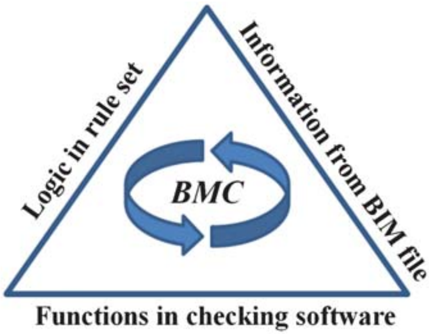


*Figure 2-4. Development of BMC solutions illustrated as interactions between rule set, BIM file and checking software.*

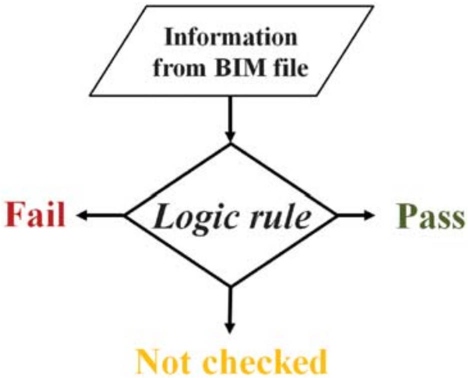


*Figure 2-5. Principle of BMC.*

update and change the embedded rule set to adapt to requirements in the project. A separate study of rule set for content checking is presented in the 'Survey of automatic checking of Statsbygg's BIM requirements' section. The AutoCode project from Fiatech (2012) can be regarded as an example of the separate development of rule sets.

## Logic in BMC

A rule is basically a simple logic question answered with 'Yes', 'No', or 'Not checked' if not activated due to missing information. The flow is illustrated in Figure 2-5. 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.

### BMC in Authoring (Design) Software

BMC does not have to be done in separate software. Object-based or BIM-based software has embedded rules for model-checking. These rules are, for example, that a door or window must be placed in a wall, or that a wall cannot start or end in a door or a window. However, further development of design rules can be regarded as part of the BMC concept.

### Modelling Practice – Content and Structure in BIM Files

Another example of poor modelling is a stair modelled as a number of small slabs. This influences quantity-take-off and model checking, but not necessarily the visualization. The quality of information, regarded as correspondence between the BIM file and rule, is addressed in this chapter. Information in BIM can be adjusted by the classification functionality in the model checking software or by adding objects and/or attributes in the BIM authoring tool (e.g., Revit, ArchiCAD, and others), and then redoing the BMC.

## CLASSIFICATION OF BMC

### Harmonized Understanding of BMC

BMC can be used as a wide and inclusive term, enabling BIM to cover both simple clash detection and the advanced code compliance verification processes. Compliance checking, rule checking, code checking, clash detection, collision control, and validation control are used as synonymous terms for model checking, but without further specification, precise and joint understanding can be hard to achieve.

To support joint understanding, the following two frameworks are introduced:

- **Framework: The four types of model checking concepts**
  Model checking is not a clearly defined term. It is primarily understood as clash detection or compliance checking, but this understanding limits the scope of model checking. Table 2-1 from Hjelseth and Nisbet (2010) presents a framework, which extends the use of model checking into four main categories based on intention and type of result.

  A) *Compliance model checking*. This is the "default" understanding of BMC (and therefore important to be aware that this is not the only one). This type of checking is based on comparing the model with pre-defined criteria. An example of this type of rule says that a minimum acceptable door width is 800 mm or more. Compliance is reached if the minimum width is larger than required width.

  B) *Guidance*. The intention of this concept is to guide the designer to consider a larger range of most-used solutions according to best practice rules. This is particularly relevant in spheres where the designer is not an expert. The checking is based on two elements: rules which identify the

*Table 2-1. Framework for model checking concepts (modified version based on Hjelseth and Nisbet 2010)*

| *Intention with model checking* | *Checking* | *Result* |
|---|---|---|
| A) validating compliance | Compliance | pass/fail |
| B) guidance to technical solutions | Guidance | proposal |
| C) adaptation of objects | Intelligent objects | adapted object |
| D) validating content of information | Content | present/missing |

situations where problems occur, and a presentation of a list of possible solutions. This type of checking is closely related to best practice a decision-support systems, but so far this concept has not been implemented within the construction industry.

C) *Adaptive model checking.* Active objects or intelligent objects are an alternative description for this type of checking. The intention is to let the object itself register its environment and then adapt automatically by following embedded behavior rules. Adaptive model checking can be divided into object adaption and system adaption. One example at object level implemented in most BIM authoring tools can be a rule that says you must always place doors or windows in a wall. This, and likewise features, are implemented in most BIM authoring software. One example at the system level could be if the building shall comply with accessibility regulations, all door widths have to be adjusted to be a minimum of 800 mm.

D) *Content checking of information in BIM file.* Content checking can be regarded as a declaration of delivered information. The intention here is to examine the BIM model for a specific purpose. The filtering rules can be used for reporting relevant information. The information can be further analyzed in BMC software, spreadsheets, word processors, and databases in flexible ways. The use of Construction Operations Building Information Exchange, COBie (East 2013), can be regarded as a light variant of this type of model checking. An example of implementation is presented in the 'Study of degree of automatic processing of Statsbygg's BIM requirements' section later in this chapter.

- **Framework: Taxonomy for classification of BMC maturity**
BIM based model checking can be from simple clash detection as supplement for manual checking, to checking of multiple integrated models who replace manual checking. However, it is so far not established a joint terminology that states level of model checking, and this make it difficult to understand the extent in use of BMC. This chapter presents a framework to determine level of BMC. Research by Succar (2009) about BIM maturity has been used as framework for development for the five level BMC maturity model. An overview of the five levels and corresponding description is presented in Table 2-2.

*Table 2-2. Levels of BMC maturity*

| *Level* | *Description* |
|---|---|
| Level 5 | pervasive model checking |
| Level 4 | integrated model checking |
| Level 3 | specific purpose checking |
| Level 2 | adjusted model checking |
| Level 1 | clash detection checking |

Note: This framework for BIM maturity covers type A) validating compliance checking and checking of type D) validating content of information from previous section.

These five levels are used as label for classification of BMC maturity. The taxonomy for classification of levels of BMC maturity is based on two criteria (taxa):

- content of information in the BIM file (increased 'the I in the BIM')
- complexity in the rules/rule set (increased intelligence in the rules)

The relation between these two criteria is illustrated in matrix in Figure 2-6.

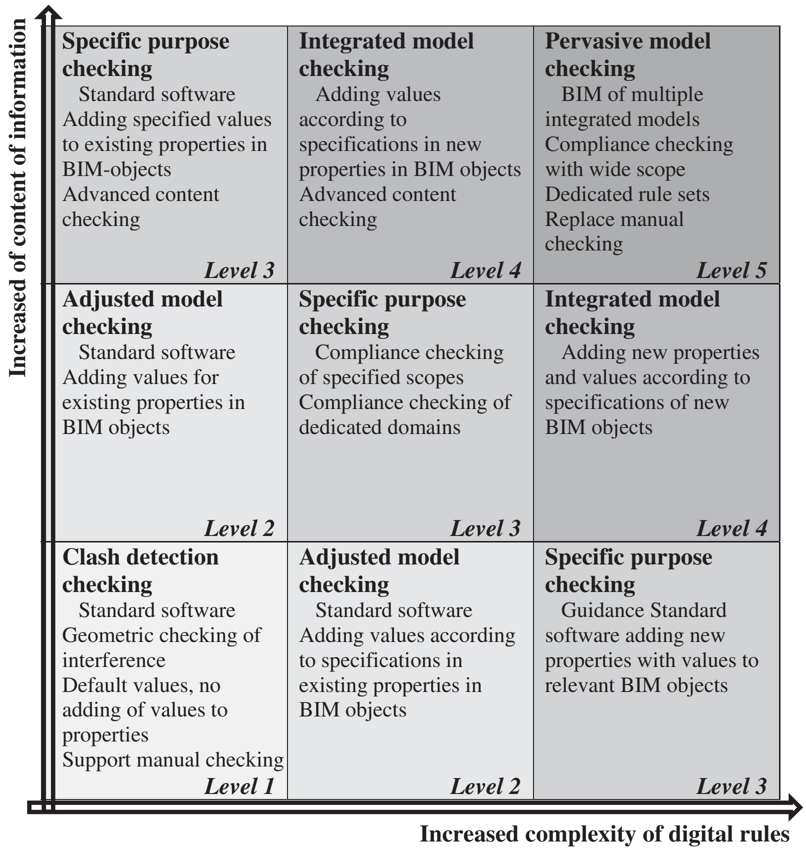


*Figure 2-6. Classification of levels of BMC maturity.*

*Table 2-3. Overview of BIM-based model checking software*

| *Software* | | *Link for more information* |
|---|---|---|
| Commercial | Autodesk Navisworks Manager | http://www.autodesk.com/products/autodesk-navisworks-family/overview |
| | Bentley Projectwise Navigator | http://www.bentley.com/en-US/Products/ProjectWise+Navigator/ |
| | Commercial BIM-servers | more developers–no one listed |
| | dRofus – Nosyko | http://www.nosyko.no |
| | Solibri Model Checker | http://www.solibri.com |
| Free | BIM-viewers | http://www.ifcwiki.org/index.php/Free_Software |
| | Open source BIMserver | http://bimserver.org |
| | Tekla BIMsight | http://www.teklabimsight.com |

The level of BIM can be classified based on content of information and complexity in the rules. Classification into middle levels; 2, 3 and 4, of maturity can be achieved by with variation of the two criteria. Which of the criteria is highest will be related to the use in projects. Benefit from use of BMC can be achieved from level 1.

## BMC SOFTWARE

### Overview of Software in the Study

The history of BMC is closely related to the development of BIM in general and specially to openBIM using the IFC format. The development of BMC software is therefore fairly new, with an increasing number of software developers. The Autodesk product that Navisworks has used for over ten years for clash detection uses input from various formats. Solibri can be regarded as the first true openBIM-based model checking commercial software accepted in the market. Table 2-3 gives an overview of some BIM-based model checking software.

### Overview of Functions in BMC Software

Table 2-4 gives an overview of functions in BMC software. The overview does not test the quality or user friendliness for the software functions. This is not a test ranking the best software, as this depends on the purpose of checking.

## SURVEY ON AUTOMATIC CHECKING OF RULE SET

### Content and Development of Rule Sets

Khemlani (2011) points out that rule sets are the cornerstone of BMC. The International Code Council (ICC 2009) presented SMARTcodes as the 'Tools of Today and Tomorrow' in 2009. The concept of intelligent codes (SMARTcodes) is an initiative of the ICC in coordination with the buildingSMART Alliance. The objective was to automate a code compliance check, which takes the building plan as represented by a building information model (BIM) and instantly checks for code compliance via model checking software. This project ended in 2010 due to lack of funding (Refvik 2013).

The proof-of-concept report from the AutoCode project in March 2012 by Fiatech indicates that this aim is still relevant. 'ICC and Fiatech are committed to completing this long-term project', said ICC CEO Dominic Sims. Using technology for code checking is a win-win for the jurisdiction, designer, and property owner, according to Fiatech (2012). This project was highlighted in the study by Refvik (2013) as an important contribution for the development of computable rules. Projects like AutoCodes can therefore have significant importance for the development and implementation of digital rule sets in BMC software. The market for rule-set is currently limited as it was with BIM objects (windows, doors, and furniture) some years ago.

Developers of BMC software offer different packages adapted to design and professional disciplines. There are a number of barriers, such as no standardized procedure for converting design rules and regulations into digital rules. BIM guidelines are mainly developed by national organizations like GSA (2007) and NBIMS (2007) in the US, BSI (2013) in the UK, Senate (2012) in Finland, CRC Q2
(2009) in Australia, and Statsbygg (2011) in Norway.

BuildingSMART International has developed a number of specifications for content in BIM files called Information Delivery Manuals (IDM 2013). The American Institute of Architects has established the 'Level of Development' (LOD) as a useful framework for specifying required information (AIA 2012). Due to their focus on specific information, these types of specifications act as a foundation for developing rule sets. Statsbygg has also taken the initiative to develop a rule set in the Solibri Model Checker based on their BIM guidance version 1.2. This initiative is presented in the next section.

The following ISO standards can be used for advice or as guidance in the development of digital rules. ISO 29481-1:2010 Building information modelling – 'Information delivery manual – Part 1: Methodology and format' (ISO29481-1: 2010) presents principles for business rules and validation rules in Clause 5. ISO TS12911:2012, 'Framework for building information modelling (BIM) guidance' (ISO TS 12911: 2012) points out control as one of three key elements for specification of information. As this selection of highly relevant resources illustrates, model checking has a strong focus on BIM guidance and standards.

Q3

*Table 2-4. Overview of functions in BMC software*

| | *Software* | | | | | | |
|---|---|---|---|---|---|---|---|
| *Functions* | *Solibri Model Checker*[2)] | *Autodesk Navisworks Manager* | *Bentley Projectwise Navigator* | *Tekla BIMsight* | *dRofus Nosyko* | *Open source BIMserver*[4)] | *Free IFC viewers*[5)] |
| Functions | | | | | | | |
| Clash detection | x | x | x | x | | x | |
| Compliance checking | x | | | | x | x | |
| Content checking | x | | | | x | x | |
| Search function | x | x | x | x | x | x | x |
| Reporting | x | x | x | x | x | x | |
| Quantity take off | x | x | x | | x | x | |
| Time liner | | x | | | | | |
| Animations | | x | | | | | |
| Exchange formats | | | | | | | |
| Import of BIM file | IFC, DWG | Almost all formats | DGN, DWG, PDF,[3)] | IFC | IFC | IFC | IFC, DWG, others |
| Direct link Revit | | x | | | x | | |
| Direct link ArchiCAD | x | | | | | | |
| Export of reports | PDF, XLS | PDF, HTML, XLS | PDF | | | IFC, others | |

*(Continued)*

*Table 2-4. Overview of functions in BMC software (Continued)*

| | *Software* | | | | | | |
|---|---|---|---|---|---|---|---|
| *Functions* | *Solibri Model Checker*[2)] | *Autodesk Navisworks Manager* | *Bentley Projectwise Navigator* | *Tekla BIMsight* | *dRofus Nosyko* | *Open source BIMserver*[4)] | *Free IFC viewers*[5)] |
| Rule sets | | | | | | | |
| Separate rule sets | x | | | | x | x | x |
| Modify existing rules | x | x | | x | x | x | |
| Combine rules to new rule sets | x | | | | x | x | |
| Develop new rule sets | | | | | x | x | – |
| Cost | | | | | | | |
| License cost[1)] | Pro | Pro | Pro | Free | Pro | Free | Free |

Notes:
1)Software license may vary depending on local/national market. Pro indicates that the cost of license is high and for permanent use in the company, not for use in only one (small/limited) project.
2)Solibri has developed integration with COBie (AECMAGAZINE 2013).
3)Bentley Projectwise Navigator can import point cloud data (Bentley 2012).
4)Services have to be programmed as database queries.
5)Viewers are free and can be used for viewing the BIM. Viewers are easy to use and can reduce the need for drawings on site. The viewing model is also possible on tablets.

## Automatic Processing of Statsbygg's BIM Requirements

This study focused on the degree of automatic processing of digital rule sets based on the BIM guidance from Statsbygg, Norwegian Public Construction and Property Management Agency. Statsbygg has developed BIM guidelines since 2008, and the current version, 1.2, is their third edition. It is available in both Norwegian and English versions (Statsbygg 2011). BIM guidance is used as a mandatory requirement for BIM projects. The BIM guidance document contains 131 requirements for the specification of information in the IFC file. These requirements were implemented as a separate rule set by Solibri Model Checker, and are included in Version 7 and newer. After first glance in Solibri Model Checker, it is easy to believe that all requirements in the BIM manual version 1.2 from Norwegian Statsbygg are implemented and can be checked automatically. However, it is quite demanding to develop computable rules, and it is therefore too optimistic to expect that all requirements are directly computable.

To determine the degree of processing, all rules in this rule set in Solibri Model Checker explored and classified whether the requirement was able to be:

- *Automatically processed*. The requirement in the BIM guidance corresponds directly with IFC data model. The rule can be processed automatically to fulfil the requirement.
- *Partly automatically processed.* The requirement in the BIM guidance corresponds partly with IFC data model. The rule is processed, but fulfilment of the requirement must be verified manually.
- *Suggested to be processed manually*. The requirement is not implemented as a processable rule but only as information in the rule set. The requirement requires either information that is not specified in the IFC data model (e.g., Norwegian specifications) or is too complicated (or expensive) to be implemented as a rule. The requirement must be verified by manual inspection of the building information model (e.g., by looking at the file in an IFC viewer).
- *Requirements was not specified or documented*. There was no information about the requirement, just missing from the rule set. The user must find the BIM guidance document and interpret the requirement, whether this is relevant in the project and where it can be verified manually.
  The results from this study are presented in Figure 2-7.

This rule set is based on input of information in an IFC 3x2 file IFC file. The outcome identified that 35% of requirements could be automatically checked, 13% partly automatic/manual, 33% could only be checked manually, while 19% of the requirements were not implemented as digital rules at all. This indicates that approximately half of the requirements can be checked automatically and verified, while the other half of the requirements have to be checked manually. It is therefore important to be aware that only parts of the requirements can be checked automatically. This type of model checking

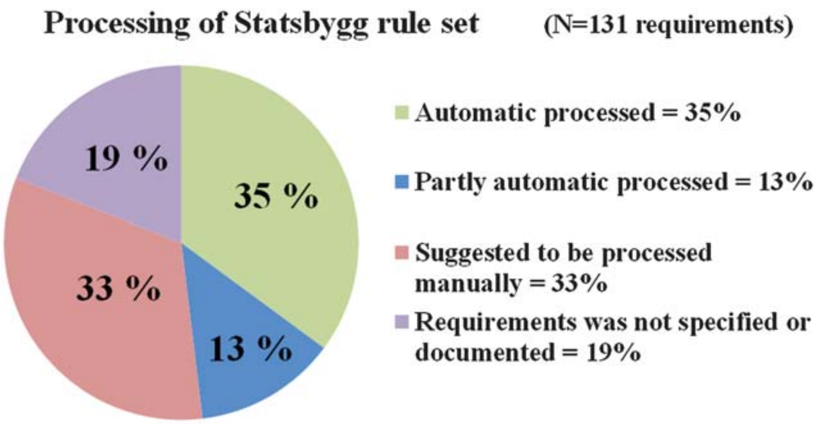


*Figure 2-7. Distribution of processing of BIM requirements in Norwegian Statsbygg BIM guidance Version 1.2.*

can be regarded as an example of 'content checking of BIM file' previously presented in this Chapter.

## Degree of Automatic Checking of Regulations

Hjelseth (2012) performed a study of the ISO21542:2011 accessibility and usability standard (ISO21542:2011), which identified 720 rules within the 152 pages. The study showed that 57% of the rules were prescriptive and could be directly converted into computable rules. Of the remaining rules, it was possible to transform about half of them into computable rules for automatic processing. The transformation was done by a mapping method. The conclusion of this test was that 17% of the total number of rules had to be interpreted manually, while 83% were applicable for BMC. The result indicates that performance-based regulation is not a barrier for BMC.

Practical use of this type of checking can be illustrated by the Solibri Model Checker, which has implemented Clauses 8, 10, 11, 12, 13, 18, 19, 26, and 33 from the ISO/DIS 21542 version (DIS stands for Draft International Standard and is a version of the standard, which is under development). The result from the check is shown as a list of red, orange, and yellow triangles in Solibri Model Checker in Figure 2-8. Looking into one of the issues by clicking on the line with a triangle, the 'Results' and 'Info' windows become activated. Clicking on the clause '18.1 Door and doors furniture' (related to the clause in the ISO standard), only door and belonging wall objects are displayed. All other elements are removed. This situation is illustrated in Figure 2-8. This contributes to identifying, for example, the issue, 'Revolving door is not accompanied by swing door', in a visual way. How this issue can be solved in practice must of course be discussed in the design team meeting or in coordination meeting. Solibri Model Checker only identifies possible issues – it does not propose possible solutions; professional skills are therefore still needed.

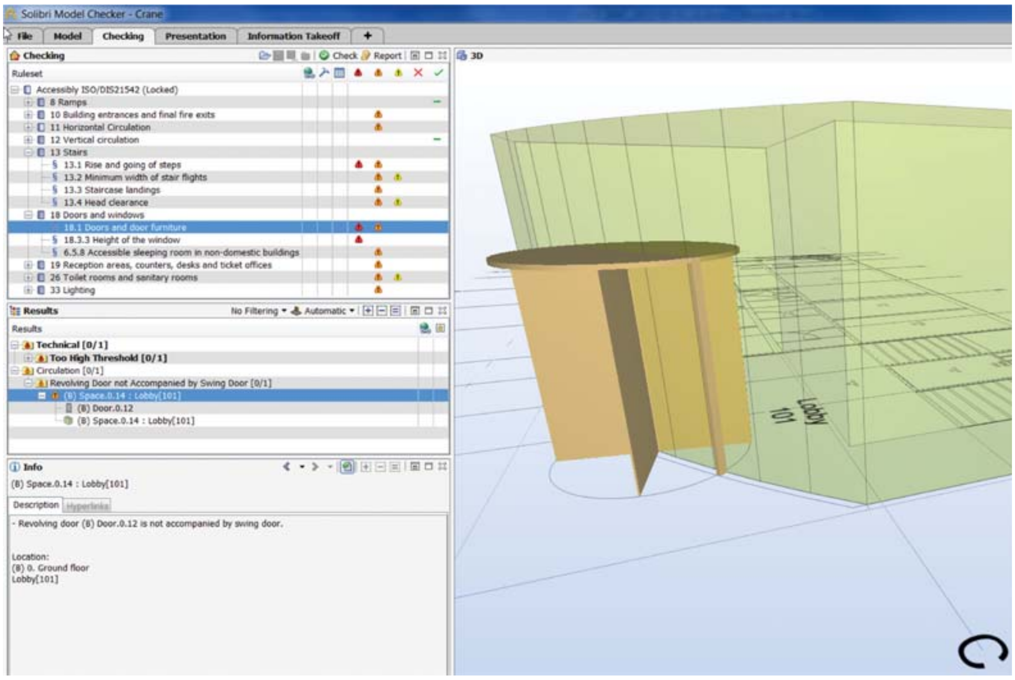


*Figure 2-8. Checking of accessibility in Solibri Model Checker (Hjelseth 2012).*

## USE OF BMC SOFTWARE AND PROCESSES IN NORWAY

### Motivation for the Case Study

The intention of this study was to explore experiences – 'Best practice' – and to identify suggestions for the further development of BMC solutions. The outcome can be regarded as an indication of how the leading-edge companies (in Norway) are utilizing BMC in today's projects (possibilities/challenges/ problems) and what they regard as opportunities of tomorrow. The study does not focus on exploring a specific project in each company; instead, it focuses on the general use of BIM and BMC. It does not cover constraints like the type of contract, split of risk and profit, number of involved partners, or number of subcontractors. All companies' feedback was based on experience from 'real BIM projects', which had a high focus on both process and utilization of BIM-based software. The respondents were regarded as the most experienced BIM experts in their companies.

The Norwegian construction industry has a high focus on the use of BIM, especially openBIM-based exchange of IFC files. Public builders like Statsbygg (Norwegian Public Construction and Property Management Agency), Forsvarsbygg (The Norwegian Defense Estates Agency) and Helsebygg (Norwegian Hospital Development Project Agency) have demanded BIM in selected projects since 2007 (Statsbygg 2007). Statsbygg announced in spring of 2013 that they had signed a 'Joint Statement' about the use of openBIM (IFC) in all projects from 1 June 2016 (BuildingSMART 2013).

*Table 2-5. Overview of commercial and public companies in the survey*

| *Category* | *Commercial/public companies* |
|---|---|
| Public serial owners/builders | Statsbygg |
| | Forsvarsbygg |
| | Sykehuset Østfold |
| Architects | Link Arkitektur |
| | Nordic |
| Consulting engineers | COWI |
| | Multiconsult |
| | SWECO |
| Contractors/property developers | AF-Gruppen |
| | NCC |
| | Skanska |

### Research Method

This study intends to identify best practices for the utilization of BMC. Table 2-5 presents an overview of the selected companies in this study. All companies are representing the-state-of-the-art in utilization of BIM and BMC. They are among the largest companies in their branch of the construction industry in Norway.

A questionnaire was sent by e-mail one week in advance of the telephone interview. This qualitative approach tries to extract understanding, experiences and common elements, rather than quantifiable statistical data. Anonymity was granted to motivate open feedback on problems and challenges.

## RESULTS OF THE INTERVIEWS WITH THE BMC COORDINATORS

### Qualitative Approach: Expert Experiences

This is a qualitative study with a focus on extracting experiences from the most skilled users of BMC in Norway. Highlights from the interviews are therefore presented to give an understanding of how BMC is utilized on demanding projects. The questionnaire was structured into six themes, with separate questions, and used as a framework during the interviews.

#### *Questionnaire Theme 1: Type of Company and Projects*

The survey included most disciplines involved in construction projects. An overview of the interviewed companies was presented in Table 2-5. It was expected to get clear differences between the disciplines, but the survey did not indicate this effect. All companies were large and with high profile in use of BIM, and in this respect heterogeneous. On the other hand, it did identify a change in roles, and especially that building owners were very active. This can be explained by model checking done by professionals in the company with long experience and high competency. This was especially clear for the building owners having an active role in demanding BIM-based deliverables. Limited competency in the company, both BIM and BMC, was pointed out as a barrier for collaboration and increased level of use.

### *Questionnaire Theme 2: Use of BIM and BMC Software*

All companies had experiences of five or more years with BIM-based projects, varying in levels. The share of BIM projects is increasing, from use of BIM only on special projects to its use on most projects by default. All companies in this survey work mainly with large projects with more than $10 million USD. However, most projects were done in collaboration with ordinary companies without a high focus on BIM beyond the use of commercial BIM-based software as drawing tools. An overview of software is presented in Table 2-6.

The focus in this study was on advanced use, development, or adaption of rule set and future perspectives from the BMC coordinators in state-of-the-art projects. It did not focus to determine extent or combinations in use of different software. Use of IFC – or openBIM – has in general a very high standing in Norway. Use of IFC-based software, such as Solibri Model Checker, is therefore regarded as a default file format in multidisciplinary projects. All 11 companies used Solibri Model Checker but also other software like Autodesk Navisworks. Navisworks was dominant on the infrastructure project due to its capacity to import a large number of file formats. Free versions of IFC viewers were used when the project management wanted to distribute the BIM file for individual presentations.

One very interesting observation was that the number of Solibri Model Checker and NavisWorks licenses was very limited compared to use of other licenses. Model checking and model coordination was generally performed by one to three participants, utilizing one or two licenses. This was also the situation in large projects with multiple disciplines from architecture, engineering, and contractors, counting over 100 professionals. This was not an expected result regarding the high BIM profile in all of these projects. Traditional organization and low awareness in utilization of BIM and BMC were mentioned by the respondents as possible explanations.

### *Questionnaire Theme 3: What is BMC Used For?*

This theme focuses on identifiable deliverables related to the use of BMC. BMC was used in all phases where BIM was used and not only as a check of final design. Clash detection and coordination of different model files (disciplines) was the default use reported by all respondents. The companies confirmed that merging different IFC files into one presentation of the project was quite common (multi-disciplinary coordination). The outcome was a coordination report, which illustrated identified issues based on screenshot functionality, and included a description of the problem, possible solutions, responsibility for following up, and

*Table 2-6. Use of BMC software in the Norwegian study*

| Type of company/ organization | Category of software | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | BIM-based model checking software | | | | | BIM-authoring (design) software | | | |
| | *Solibri M C*[1] | *NavisWorks*[2] | *Tekla BIM Sight*[3] | *dRofus*[4] | *IFC viewers*[5] | *Revit*[6] | *Archicad*[7] | *Tekla Structures*[8] | *AutoCAD Civil 3D*[9] |
| Public serial owners/builders (N = 3) | 3 | | | 3 | 3 | | | | |
| Architects (N = 2) | 2 | | | | | 1 | 1 | | |
| Consulting engineers (N = 3) | 3 | 2 | | 1 | 3 | 3 | 1 | 2 | 2 |
| Contractors/property developers (N = 3) | 3 | 2 | 2 | | 3 | 3 | | 2 | 1 |
| All respondents (N =11) | 11 | 4 | | 4 | 11 | 7 | 2 | 4 | 3 |

Notes:
BIM-based model checking software:
[1]Solibri Model Checker All use based on IFC import
[2]NavisWorks Used only on infrastructure projects
[3]Tekla BIM Sight Used as supplement to Solibri MC, and as a 'free IFC viewer'
[4]dRofus Only used by public builders on large projects, and consulting engineers in hospital projects,
[5]IFC viewers
BIM-authoring (design) software:
[6]Revit Includes both Architecture and Structure versions
[7]Archicad Only used by architect
[8]Tekla Structures For structural constructions
[9]AutoCAD Civil 3D Used only on infrastructure projects
Mostly free versions of Solibri Model Checker and Data Design IFC viewer (Norwegian)

deadline. All respondents that used Solibri Model Checker highlighted that the reporting functions replaced traditional minutes. These types of reports were very useful for collaboration and saved time in reporting and discussion afterwards. BMC was regarded as a part of the QA package. Some companies used the information take-off functions, e.g., in Solibri Model Checker, for quantity take-off (QTO) and the further calculation of material and works.

Utilization is related to traditional quality assurance and not to new digital services. The checking software itself is easy to use, and the license cost could be saved by avoiding one single construction mistake. However, it was reported that it was hard to get directly paid for BMC. Even if the benefits from savings were very significant and positive for the overall project, the contracts were separate for each discipline. Type and design of the construction contracts plays a major role for collaboration and how changes become solved. National differences may influence the method of collaborating. In Norway, a contract for construction is often split up among a number of sub-contractors, who in turn use other sub-contractors. This is also the situation when one large contractor has won the entire contract. The attitude was: 'I do my job and get paid for that – not for what happens afterwards'.

Another interesting piece of feedback from one respondent was that there were very few practitioners who took their own BIM and merged it with others in order to explore coordination and content. Lack of 'curiosity' should perhaps line up as a barrier, or can the business model be blamed?

### *Questionnaire Theme 4: Procedures for BMC*

BMC was regarded a part of the quality assurance (QA) system of the model and of the project. QA traditionally uses written procedures, and this approval was applied to BMC procedures as well. The extent of using this practice had some variations, but all companies used written procedures in combination with best practice experiences.

BMC was not included in contracts, while the mandatory use of BIM guidelines was. BIM guidance had references to BMC regarding when and what should, or must, be BIM deliverables. BMC was not regarded as a separate deliverable but as a part of the process and a way of utilizing BIM. The procedure executing a BMC procedure can be divided into the following three parts:

- *Quality of BIM deliverables*. These specifications were covered by the company's BIM-guidance.
- *Procedures for QA*. BMC is following established QA procedures. Best practice for coordination meetings is included in these procedures.
- *Scope and content in rule set*. This was not documented as the company reports. This development was done by the BIM coordinator, BIM manager, or participants with experience with BMC. This development was based on experience and best practice.

The close connection between BIM and BMC was expressed by the following type of statement from one company: 'Use of BMC can be regarded as an indicator for BIM-maturity'.

Projects using BMC (in Norway) are regarded as real BIM projects because everyone has to deliver BIM files in IFC format to be merged into the model checker (based on Solibri Model Checker). There are no needs of drawings for coordination of design – this was done by use of models.

Processing of BMC was done by a very limited number of participants in the project. Even in very large projects – over $100 million USD –operating the BMC software was normally limited to 1–3 participants working on the project management team. The software, like Solibri or Navisworks, is easy to operate. Arguments for limited use are related to contracts and responsibility for coordination.

Presentation of the issues after a clash detection check always need some time – 2–4 hours – of preparation by an experienced operator. Too high a sensibility in the rule sets results in an excessive reporting of non-relevant issues. This makes it hard to know which issues are relevant or not. Preparation was therefore a mandatory part before presentations of the outcome.

One interesting observation was some changes in the scope of disciplines. The building owner – in this case, the public builder of hospitals – took a very active role in the use of BIM and coordinating the BIM models. Closer collaboration among all roles was also a general feedback given from the use of BMC.

### *Questionnaire Theme 5: Use of Adapted Rule Sets from Solibri Model Checker*

This survey was not focused on testing specific software, such as Solibri Model Checker. On the other hand, Solibri Model Checker can be used to illustrate the concept of separate rule sets in the checking software. Rule sets can be regarded as commercial goods, such as objects of building parts. So far, they are only an embedded part of Solibri Model Checker. Users can modify existing rule sets and save these separately for their own use. No companies, except Statsbygg, have developed a rule set from the ground up. Statsbygg have developed a digital rule set in Solibri Model checker for compliance checking with their BIM guidance. This was previously presented as 'Study of degree of automatic processing of Statsbygg's BIM requirements' in this chapter. The respondents explained that the need for development of new customized rules was solved by modification and adaptation of existing rule sets. This did the job at low cost and in a short amount of time – and was often "good enough". Another reason was that development of new rules required a lot of skills and the fact that the technical implementation had to be performed by Solibri Model Checker.

All respondents had modified the embedded rule set to minor or major degrees. The modification was done as a selection of separate rules into a new rule set more adapted to the need in the project. In addition, some constraints were modified, e.g., distances to be longer or shorter than in the embedded rule set. Dedicated rule sets, such as accessibility based on ISO/US requirements and other rule sets based on regulations, were not regarded as relevant for Norwegian projects, and were therefore not in use.

This study identified that it was mainly following rule sets in Solibri Model Checker, which were modified and adapted to company/project related rules:

- 'General Intersection Rule' for checking collisions between technical subjects, architectural, and structural models
- 'Components are filled' for checking consistency between architectural and structural models
- 'Components fit in architectural ones' for checking consistency between architectural, engineering and MEP models
- 'Comparison' for checking changes in a revised model

As the titles of the above rule sets indicate, these rule sets are based on variations of clash detections for making this type of verification more relevant for Norwegian requirements. Another motivation for adapted rule sets was to reduce the amount of feedback from of non-relevant issues.

### *Questionnaire Theme 6: Highlights – Open Questions and Free Answers*

The two main overall questions asked in the interviews were:

a) What is the most positive effect of using the model checking software?

b) What is the most challenging aspect of using the model checking software?

**a) What is the most positive effect of using model-checking software?** Q4
This question focuses on positive experiences from real projects.

All respondents stated that BMC is a very useful collaboration tool merging different model into one joint model – visualization was very important. Use of BMC gathered the project team to a joint presentation of the project. It was the combination of process and program which made the power for the participants in the project. The outcome of the validation – the model checking in itself – was regarded as 'guidance' for identifying issues.

The respondents said that BMC makes them focused on solutions – issues are identified at a stage where they can be solved without redoing work. All involved in the project see the same 3D model or building information model; this is far easier to understand in a short time than drawings. It was reported by some respondents that the volume of traditional 2D drawings has been dramatically reduced. A combination of drawings and models are often used on the construction site. As one respondent expressed, 'BMC makes a new daily routine for the project coordinator'.

The feature to produce issue reports or coordination minutes was regarded as a very important function of the BMC software. This feature was used for collaboration and management of who shall follow-up which issue by deadline. Some of the respondents thought that BMC had the effect of a learning tool. It gave feedback on correct modelling and structuring of information in the authoring BIM software.

**b) What is the most challenging use of model checking software?** This question focused on both experiences from real projects and obstacles aiming for increased ambitions in future projects.

The most important drawback was that Solibri Model Checker identified too many false issues. It takes time to prepare and eliminate non-relevant issues before presentations. It contributes to reducing the impression of reliable verifications. An aspect of this is that 'BIM is not always BIM' as one respondent expressed it. There is a large variation in how the IFC implementation is done in different software and software libraries – and also how the designer is modelling and structuring (entering) information in the BIM software. This makes more advanced testing unreliable and confirms the 'garbage in/garbage out' principle. One respondent stated: 'Solibri Model Checker rule sets are powerful tools that identify almost everything in an assembled model of more BIM files (e.g., in multidisciplinary project). If you are sloppy with putting limits in what to be checked, it soon becomes a mess about what the rule set include of rules (that in principle can be checked), the content of object with relevant information in then BIM files (what can be checked in practice), and how this is reported by the checking software (priority of actions). The procedures of rule checking are critical for the outcome.

Multidisciplinary coordination requires that BIM from the different disciplines are at same level of development (LOD) or are in the same phase to perform BMC. Often, one discipline will start designing when other disciplines have reached a stated level. This requires dedicated rule sets, because rule sets are normally based on the final design.

Lack of flexibility was mentioned by some respondents as a challenge. It was reported that it was not possible to check only specified parts of a model ('zone of control'), specific disciplines, or other partial elements without preparing the BIM file in advance. Better tools for management of information were wanted. The classification function in Solibri was useful and easy to use, but a good and joint system for classification was often hard to develop.

Some respondents reported that a collision (issue)-free model often was regarded as a good solution, and stopped further development. A model free of issues can, at its best, be verified as 'not bad', but never as good. This can only, with BMC of today, be done by skilled practitioners. The required effort for closing the chasm between the level of today and higher-level BMC was expressed by some respondents as a leap in level, i.e., more than incremental development. To reach the BMC level where one trusts the outcome of a check 100% without visual control requires full control of all steps, both in process and program. One of the respondents expressed this as going from tricycle to bicycle – this requires a number of new skills. However, the companies in this study use BMC at a level far above the general use of BIM and clash detection.

Many respondents reported a lack of design objects or object libraries with joint and missing comprehensive content of information as a critical problem for multidisciplinary coordination. This was in projects solved by 'bypasses' and a high focus on discipline and joint manual input. Specific building parts were identified by type number, ID-codes, and similar solutions of manual input. This was hard to maintain for all parts in the project, but easy to violate.

### Highlights from the Survey

All respondents stated that clash detection was the most frequent use of BMC. Reporting on many irrelevant issues was a challenge and involved time to prepare the presentation of the outcome of clash detection for the design or coordination teams. Clash detection was very useful – almost mandatory – in the coordination of multidisciplinary projects. The capacity to produce issue and coordination reports in the coordination meeting was regarded as one of the most useful functions in the checking software. Clash detection was used to support collaboration, and BMC was regarded as a very useful collaboration tool. This finding is supporting 'Developing internal collaborative BIM procedures' as the top forecast for 2014 in the status report from McGraw-Hill Construction (2012). The level of BMC can be regarded as a maturity index for the utilization of BIM. Most advanced BIM projects also had the most advanced utilization of BMC. All respondents supported the view that BMC must be regarded as a 'mandatory tool' for the coordination of BIM projects.

Clash detection and multidisciplinary coordination represented the most typical uses of BMC. Solibri Model Checker was the most-used software for BIM files in IFC format. Autodesk Navisworks was the second most-used software, but in infrastructure projects, Navisworks was the most used on infrastructure projects due to its ability to import different file formats. All companies in the survey had modified the embedded rule sets in Solibri Model Checker and adapted them into company-specific rule sets. The benefit was better precision on what was actually checked, in addition to a reduced number of non-relevant issues. The development of digital rule sets was regarded as a challenge.

## LIMITATIONS FOR THE INTERVIEWS

The interviews of BMC experts in Norway are based on a limited selection in the forefront companies. Suggestions for future solutions have particularly been influenced by technology optimism. This is of course not representative for the construction industry. A survey contrasting these companies could be useful. This study could have focused on why companies are not using BMC, and what the decisive moment is for these companies to start using BMC in their projects.

All interviews were documented and a questionnaire was used, but the answers were mostly based on personal experiences and attitudes related to the pervasive use of BIM and BMC. Reliability is in principle ensured, but due to time and project dependency, it can be hard to repeat with identical results. On the other hand, the variation within the group was low and the main findings should be repeatable.

## CONCLUSIONS

BIM-based model checking (BMC) can be regarded as one of the best ways to illustrate the benefit of the relevant content of information in BIM files. It is a cross-disciplinary way for the coordination of BIM deliverables from different disciplines. Commercial software solutions for BMC are easy to operate and offer more functions than most users will need. Software is not delimiting the implementation of BMC in the construction industry. Implementation of BMC is highly related to the use of BIM in general and the use of openBIM based on IFC specifically. BMC requires files with relevant information to process the rules of checking. More information in the file enables more rules and exchange of information in a common format like IFC enables concentration of efforts in the development of solutions. BMC can have a high impact for development of high-quality content of information in BIM files and the use of open BIM. The level of utilizing BMC can therefore be used as an indicator for the maturity of BIM.

However, use of BMC is not a mainstream method of workflow today. Even in large companies, keeping tabs on BIM-based projects through the use of BMC software is limited to a few dedicated users (coordinators). This is a paradox since the software is easy to operate and the detection of issues is best done by experienced professionals rather than by coordinators. Lack of relevant information in BIM files, in addition to low and variable BIM-maturity in companies involved in the project, is pointed to as the main reason for limited use of BMC.

BMC is therefore mostly used as a coordination tool for clash detection, and in this way, it has a large impact on the process by identifying issues, assigning responsibility, and following up with changes. In this respect, BMC is playing an important part in the quality assurance of digital models.

Development of rule sets is a general obstacle for wider use; this is especially the case for missing rule sets of mandatory regulations and standards where BMC has the potential to replace manual and time-consuming work. The modification of existing rule sets in commercial software will cover the need in most projects. This must be supported with specification of information in BIM files.

BIM-based model checking (BMC) is a type of software solution, which has the capacity of becoming a game-changer for utilizing BIM. BMC provides a close interaction with the content of information in the BIM model and can be used as a catalyst for increased utilization of copious BIM and for sharing relevant information among all partners in a construction project.

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**Paper 7**

# Trustworthy interpretation of normative text by use of ontology

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**Trustworthy interpretation of normative text by use of ontology**

Eilif Hjelseth

Department of Mathematical Sciences and Technology, Norwegian University of Life Sciences (NMUB), P.O. Box 5003. NO-1432 Aas, Norway;
PH (+47) 64 96 54 00; FAX (+47) 64 96 54 01; e-mail: eilif.hjelseth@umb.no

## ABSTRACT

This chapter explores the use of ontology-based methods of interpreting text in a trustworthy way. The Norwegian fire regulation has been used as the sample of normative text, but the explored methods and use of examples are applicable for all types of normative text, including regulations in general, guidelines, standards, contracts, etc. The applicability of ontology-based methods and frameworks are presented by use of practical examples. Multiple methods are explored: Terminology is explored by use of Semantics of Business Vocabulary and Rules (SBVR). Various use of Resource Description Framework (RDF) is presented for development of shared vocabulary and identification of relevant information. Methods for restructuring of regulations and extracting relevant information are explored. Experiences from this study indicate that the explored methods and frameworks can be applicable for practitioners. Positive outcomes can be achieved after interpreting a limited amount of text, as part of regulations, standards, or contracts. Increased use of the ontology-based method can result in the significant improvement of practical interpretation of regulations supported by digital services.

## INTRODUCTION

**Information in the AEC/FM industry is text based – Need for trustworthy interpretation.** This chapter focuses on use of ontological methods to improve interpretation of regulations, standards, and contracts. Ontology can be regarded as a concept for shared understanding, which focuses on "what it is," and not only on "what it is called." According to Gruber (1993), ontology is defined as formal specification of a shared conceptualization. Use of ontology engineering has been presented by Beetz et al. (2008) "as a way of transforming understanding." The roles of ontology vary from knowledge management to semantic interoperability. This chapter intends to present methods and examples where an ontological approach contributes to the increase of shared understanding by use of simple methods and examples based on regulations used in the AEC/FM (architects, engineers, contractors/facility management) industry.

The AEC/FM industry is about the design, building, and maintenance of physical objects like building, bridges, roads, railways, etc. These constructions can be visualized by drawings and models, both as physical scale models and visual virtual 3-D models, in addition to building information models (BIM). BIM has the capacity to integrate visual representation with information in text and values.

However, written documents play a major role in the exchange of information in the industry. Documents often have priority over drawings when differences occur. Regulation consists entirely of written text documents without any drawings (or other visualization/graphic illustrations). Public guidelines to legislation are generally very wordy with supplemental simplified illustrations. Standards are similar, but with one exception: they typically have a separate clause for terms and definitions. Regulations, standards, and contracts are written for personal interpretation. There has been a significant development and use of digital tools and solutions for design and calculations, visualization in general, and within BIM-based software in particular. However, the situation with use and interpretation of text-based information is remarkably low. Digital version of regulations is normally synonymous with pdf or html versions of the text. This situation has therefore a high potential for improvement.

**Approach and methods.** This chapter intends to present the practitioner methods and examples that illustrate problems – and solutions. The methods for exploring terminology are based the Semantics of Business Vocabulary and Rules, SBVR, (SBVR 2014). Resource Description Framework, RDF, (RDF 2004) is used to investigate the relation for making connections (linked data) between terms. RDF enables querying of the vocabulary. The principles behind these selected methods are well defined and documented, and a number of software tools are available, free of charge, for practical use. Texts from the Norwegian regulations are used as samples – but, in principle, any document can be used. Regulations, in addition to standards and contracts, are well-suited examples due to the importance of trustworthy interpretation.

## ONTOLOGY-BASED APPROACH FOR INTERPRETING TEXT

**Interpreting text with high precision.** This chapter uses real text with high requirements for precise interpretation as samples. Text from the fire section in the Norwegian regulation system is used as sample in this chapter. However, in principle, this could be any type of text, such as contracts or standards, for which consistent interpretation is very important throughout the entire document.

The Norwegian regulation system consists of three levels: law, code, and guidelines. Fire safety and fire protection features must be regarded as an obvious aspect in the law Planning and Building Act of 2008 (PBL 2008), since it is only mentioned briefly in section 29-5 Technical requirements: “Any building with rooms for human habitation shall be satisfactory … and fire prevention, etc.” (PBL 2008). In the code document “Regulations on technical requirements for building works (technical requirements)" is the fire safety section covering 7 of 37 pages, or approx. a quarter of all technical requirements (TEK10 2010). Guidelines for the technical requirements (V-TEK10 2013) are developed by the Norwegian Building Authority (DIBK) as an interpretation of the law and codes. The guidelines' volume is 303 pages long, 75 pages, or approx. a quarter, of which are about fire-related regulations. The guidelines have approximately 10 times as many pages as the code. This can indicate that this topic is complicated and contains detailed requirements. In addition, the regulations refer to other legislations, especially the Norwegian Directorate for Civil Protection (DSB), and standards, both Norwegian and European. These references intensify the need for consistent interpretation of regulations and for the identification of relevant parts.

**Norwegian fire regulations.** This chapter is based on the interpretation of text from three cases in the Norwegian fire regulations (TEK10 2010 and V-TEK10 2013).

- Height tool
    - abstract term used in regulation which needs to be connected to terms in practical use
- Small building
    - ambivalent use of terms where one needs to be aware of which definition/interpretation is used
- Fire Hazard classes
    - system for classification, example of use of linked data

The selection of text from a Norwegian regulation has been done to relate this to situations of practical use. The scope of this study is not regulations, but the use of ontology-based methods. The presented methods should also be relevant for other types of text, such as different national regulations in other countries, standards, and contracts.

**Terminology – developing a vocabulary.** Terms in legal regulations are often expressed by abstract concepts, or a term that legal experts claim "must be interpreted in each situation." One example is the fire technical term: "height tool" used in the technical guideline (V-TEK10 2013). The guideline identifies no explicit definition, but use "fire trucks equipped with machine ladder or snorkel" as supplementary information. In the KBT dictionary (KBT 2013) (KBT is an abbreviation for "Collegium for fire technical terms," a non-public organization), "fire truck" is called "fire-fighting vehicle" and is defined as "emergency vehicle for fire department." Ladder vehicle is defined as "fire trucks equipped with telescopic ladder with or without basket on top that is hydraulically or mechanically driven ladder that can rotate 360º." Snorkel vehicle is defined as "fire trucks fitted with lifting/telescopic tool, with a platform at the top which is hydraulically driven and can rotate 360º." An example of the thesaurus is presented in table 1.

**Table 1: Example of thesaurus for fire technical terms based on “Height tool”**

<table>
<tr><th>Abstract term used in V-TEK10</th><th>Professional term in industry</th><th>Synonyms used in industry</th><th>Pre-defined instances used</th></tr>
<tr><td rowspan="7">Height tool</td><td rowspan="3">Ladder vehicle</td><td rowspan="3">Fire-fighting vehicle with ladder<br>Fire truck with ladder</td><td>Ford Fire Truck Model “Alfa”…</td></tr>
<tr><td>Ford Fire Truck Model “Beta”</td></tr>
<tr><td>MB Fire Truck Model “Gamma”</td></tr>
<tr><td rowspan="4">Snorkel vehicle</td><td rowspan="4">Fire-fighting vehicle with snorkel<br>Fire truck with water cannon<br>Fire truck with snorkel</td><td>Dodge Fire Truck Model “Delta”</td></tr>
<tr><td>Ford Fire Truck Model “Epsilon”</td></tr>
<tr><td>Volvo Fire Truck Model “Zeta”</td></tr>
<tr><td>MAN Fire Truck Model “Eta”</td></tr>
</table>

All terms in table 1 are examples of synonyms that can be used independently – if the software has support for semantic mapping. Model-checking software often has functions for classification and the development of thesauri should be applicable.

The definition of snorkel vehicle above is maybe not as useful at it looks. The definition is circular and focuses little on the “characteristic feature” of the snorkel vehicle: the snorkel. The definition states that the snorkel can rotate 360º, which will in principle exclude a snorkel that can only turn 359º. It also fails to specify whether the snorkel can turn around several times or must to reverse its rotation due to cables and hoses. This way of presenting definitions can therefore result in unintended consequences.

Working with terms and definitions are often time-consuming and definitions are often based on the consensus of a single sentence or two. There are several methods and tools that can be used to develop vocabularies. This study does not focus on technology, but on methods which can be supported by technology. A number of freeware and commercial software tools are available. Many small-scale projects can also be done without use of dedicated software.

**Semantics of Business Vocabulary and Business Rules (SBVR).** This case of terminology is based on the “Semantics of Business Vocabulary and Business Rules” (SBVR) methodology (SBVR 2014). This methodology is developed by Object Management Group (OMG), an international, open membership, not-for-profit technology standards consortium. SBVR is based on ISO 704 (2000) “Terminology work – Principles and methods” and ISO 1087-1 (2000) “Terminology work – Vocabulary – Theory and application” standards. The current version of the SBVR standard was released 4 November 2013 (SBVR 2014). The SBVR methodology presented in Table 2 uses the unique operators: Term, Fact type, and Rule. The term “Height tool” referred to above is used as an example.

**Table 2: Use of SBVR for developing vocabulary**

| Operator | Formulation |
|---|---|
| Term: | height tool |
| Term: | ladder vehicle |
| Term: | snorkel vehicle |
| Term: | fire vehicle |
| Term: | fire truck |
| Term: | ladder |
| Term: | snorkel |
| Term: | Ford Fire Truck Model “Alfa” |
| Term: | Ford Fire Truck Model “Beta” |
| *This list can be extended with more terms* | |
| Fact type: | ladder vehicle is a type of height tool |
| Fact type: | snorkel vehicle is a type of height tool |
| Fact type: | fire vehicle is a type of height tool |
| Fact type: | fire truck is a type of height tool |
| Fact type: | ladder is part of a fire vehicle |
| Fact type: | snorkel is part of a fire vehicle |
| Fact type: | ladder is part of a fire vehicle |
| Fact type: | Ford Fire Truck Model “Alfa” is a type of fire vehicle |
| Fact type: | Ford Fire Truck Model “Beta” is a type of fire vehicle |
| *Here are the relations between the terms linked up* | |
| Rule: | It is required that a fire vehicle have at least 1 ladder |
| Rule: | It is required that a fire vehicle have at least 1 snorkel |
| Rule: | It is required that a snorkel can turn 360º or more |
| Rule: | It is required that a snorkel can turn 360º or more |
| *Here are the requirements to each fact added – this list can be extended for more precise specifications* | |

The colors used in Table 2 are based on the free version called SBVR Lab 2.0v editor launched by Rulemotion (2014). The essential aspect is that this is a dynamic model that can be continuously expanded. This method leads to “linked data” referred to later in this chapter.

**Ambiguous terms.** Regulations, standards, and terms are examples of document systems that require unambiguous interpretation. A term used in one situation (context) can have a clear interpretation and contribute to a joint understanding. However, when this term is used further in the document, the interpretation can be slightly different, and when comparing different documents, this difference may further increase.

“Small houses” are an example of a term that most people have common understanding of. The general understanding in everyday language is unproblematic, but it does not draw a clear definition. When using this in conversation, one often turns to more precise terms, e.g. by referring to the small house as a “cabin” when it is very small, or “low apartment building” when the housing is larger. Written text does not have this opportunity. It is therefore important to be aware that it is an unambiguous use of the term. The following examples indicate that it is not always easy when the differences are relatively limited.

The term “small housing” is explained in the guideline for Fire protection in § 11-9 “The fire characteristics of products and materials” as: “With small housing means detached, semi-detached housing and other low constructions.” The Energy section § 14-1 “General requirements relating to energy” explained as: “Small housing in this clause include detached, two-, three- or four-dwelling, town and linked housing”. The criteria for this classification are not specified. Small dwelling housing in a vertical chain (terraced housing), from an energy point of view, are small units with separate “energy control.” From a fire protection point of view, this can represent a large building with different users. Vertical linked housing is therefore not included in the fire protection definition, or understanding, of “small housing.”

One could hope that the new Norwegian Standard NS3457-3 “Classification of construction works – Part 3: Building types” (in a series of six standards within classification of construction works) would sort this out. However, this is not the situation since the standard has a separate category for “Small housing,” where detached housing explicitly is not included. This is classified as a separate category.

The Norwegian State Housing Bank has a principal definition supplemented with some defined types of housing. The definition says:  “Small houses are homes that are physically bound together in a way where it is at least one common wall, or common floor / ceiling with neighboring dwelling. This will typically be townhouses and duplexes. Linked housing is also considered as small houses” (Husbanken 2014). This definition excludes detached houses, a common and important type of building, which in Norway are privately owned.

The term “small housing” can therefore be used as an example of different definitions related to different sources, but often used in identical practical situations. The overview is illustrated in table 3.

**Table 3: Definition of term “small housing” in relation to different sources**

| Context (source)<br>Include | TEK10 Fire clause | TEK10 Energy clause | NS3457-3 standard | Norwegian Housing bank |
|---|---|---|---|---|
| Detached housing | X | X | i) | i) |
| Semi-detached housing | X | X | X | X |
| Two- to four-dwelling housing | | X | X | X |
| Undetached housing | | X | X | X |
| Linked housing | | X | X | X |
| Terraced housing | | | X | X |
| Other low constructions | X | | | |
| General description | | | | X |

i) Detached housing is not included in small housing

Combining and comparing regulation can be a challenge. Even if an identical term is used, this is not evidence that there is a connection. The term “small housing” is used as an example. Fire protection, energy calculation, and national statistics will of course give different criteria for identification. Harmonization of terms is therefore a challenge. For traditional interpretation, this problem will be solved depending on the knowledge of the professional. However, simple digital searches have a different approach and will only identify the term (word) itself. Trustworthy use of this term requires that the context of the source is included as reference or metadata.

## DEVELOPMENT OF A SHARED VOCABULARY

**Taxonomy for re-structuring of hazard classes in TEK10.** Development of a vocabulary with consistent definitions is a good start, but, as the previous section illustrates, this is not enough. There is a need for developing a shared vocabulary. Capacity to share the terms – the vocabulary – is essential, both to connect terms that actually are related, and to show, or visualize, terms that are not connected or related.

Hazard classes are the most controlling factor for identification of requirements in the regulations. Table 4 presents the fire section of the guidance for the technical code. This table identifies the hazard class by a number of examples of different types of building for each hazard class.

**Table 4: Types of buildings in different hazard classes in §11-2 Table 1 in the V-TEK10 guideline (V-TEK10 2010)**

| Hazard classes | | | | | |
|---|---|---|---|---|---|
| **1** | **2** | **3** | **4** | **5** | **6** |
| Carport<br>Garage parking, (one floor)<br>Aircraft hangars<br>Cold storage<br>Sawmill<br>Workmen's hut | Industry<br>Chemical factory<br>Canteen, under 150 employees<br>Office<br>Livestock building<br>Underground parking<br>Explosives manufacturing | Kindergarten<br>School | Dwelling housing<br>Holiday home<br>Orphan home<br>Boarding school<br>Student hostel<br>Self-service cabin | Assembly hall<br>Sports center<br>Canteen for more than 150 people<br>Movie theater<br>Church<br>Convention center<br>Museum<br>Traffic terminal | Hotel<br>Overnight stop<br>Care institution<br>Hospitals and nursing homes<br>Cabin and hostel<br>Arrest and imprisonment<br>Asylum center |

However, even if this is a part of the guideline, it can be questioned if this is helpful to distinguish the limits between different hazard classes. The “trouble” is moved from a question about hazard class – to the type of building. An example can be the difference between: “Student-hostel” in hazard class 4 and “Cabin and hostel” in hazard class 6. Systems for distinguishing the different types of buildings have not been developed, in addition to buildings that are not listed, or combinations of the above buildings. This type of problem is presented as “facts complexity” in the BIM-based model checking section later on in this chapter. It is important to be aware that, in terminology, a term is “only” a label mapped to a definition (Hjulstad 2006). Hazard class is not determined on what the building is called, but what the building actually is. The next section presents the taxonomy for re-structuring the hazard classes in TEK10.

**Taxonomy for re-structuring of hazard classes in TEK10**. Correct understanding of the fire technical term “hazard class” is essential. Table 4 gives a number of examples of building types, but no clear definition. Table 5 presents a taxonomy based on asking four yes-or-no questions. Dependent on the answers, the use of the building (not the building itself) is classified into six different hazard classes.

**Table 5: Hazard classes as presented in the TEK10 §11-2 code**

| **Hazard classes** | Structures designed for only the sporadic presence of people | People in the structure are familiar with the opportunities for escape, including escape routes, and can get to safety unassisted | Structures designed for overnight stays | Intended use of the structure does not represent a serious fire hazard |
|---|---|---|---|---|
| **1** | Yes | Yes | No | Yes |
| **2** | Yes/No | Yes | No | No |
| **3** | No | Yes | No | Yes |
| **4** | No | Yes | Yes | Yes |
| **5** | No | No | No | Yes |
| **6** | No | No | Yes | Yes |

Table 6 is based on the questions in Table 5. However, the questions are transformed to short versions, and two of the questions are re-formulated into an inverse form.

**Table 6: Re-structure of questions used in the V-TEK10 guideline**

| Does the user / users of the building: | | | | |
|---|---|---|---|---|
| Original version | have permanent users | need assistance | stay overnight | serious fire hazard |
| Re-formulated version | sporadic use | need no assistance | overnight | serious fire hazard |

Figure 1 presents a graphical view of the outcome, organized as a decision tree of the four answers in Table 5. The hazard classes are not organized in an increasing order. Hazard class 2 has dual representation and indicates that this is not a relevant criterion (question) for classification.

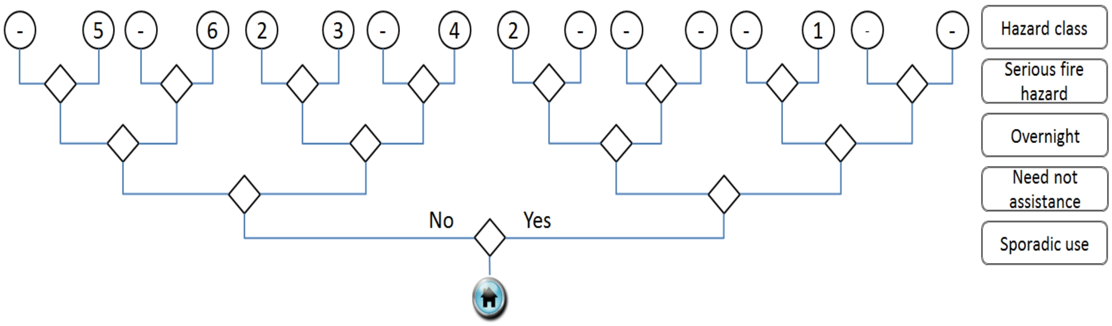



**Figure 1: Graphical representation of original questions for identifying hazard class**

Figure 2 illustrates the situation after re-organizing the questions to optimize for the simplest path in decision-making. Two questions are reversed to get an increased numbering of hazard classes. Based on making a decision, this is not necessary. However, it illustrates the logic behind the increased numbering of hazard classes. Hazard class 2 is a "separate branch" and could be re-numbered to get an increased numbering. After this re-organization, no questions lead to "empty classes".

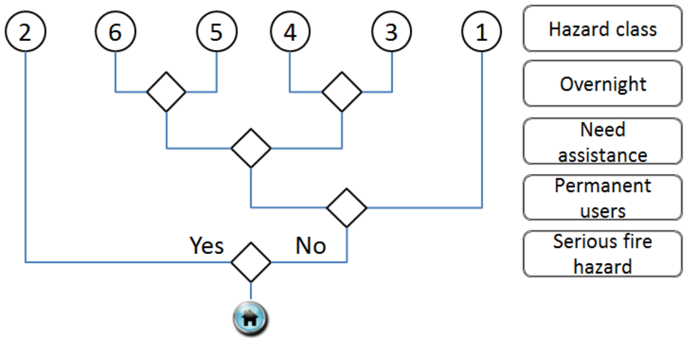



**Figure 2: Graphical representation of re-structured questions for identifying hazard class**

## LINKED DATA - CONNECTION BETWEEN THE TERMS.

**Linked Data.** The enumeration over hazard classes in Table 5 covers most types of buildings and is easy to use. However, based on the study in the previous section, one can declare that Table 5 "Types of buildings" is in principle as "unnecessary". There will always be border cases. Furthermore, the criterion is not what one names the building. Using the naming or the "power of definition" to get the project in a "convenient" class is a well-known method. For a clear interpretation, the characteristic criteria must be used. Hazard classes have a well-defined taxonomy. The number of six hazard classes (see Table 5) was defined in advance, not as a consequence of the criterion. The Resource Description Framework (RDF) is a standard model for data interchange on the Web (RDF 2004). 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 a RDF triple is presented in Figure 3.

| | | | |
|---|---|---|---|
| RDF is linking data by making triples: | *hazard_class* | *related_to* | *building_use* |
| "Subjects" can be "objects" for further linking: | *subject* | *predicate* | *object* |
| The "triples" data model: | *building_use* | *has* | *serious_hazard* |

**Figure 3: Hazard classes presented as "triples" in data model, RDF.**

**Hazard classes structured as triples.** In computing, linked data (often capitalized as Linked Data) describes a method of publishing structured data so that it can be interlinked and become more useful. This data builds upon standard Web technologies, such as HTTP, RDF, and URIs. However, rather than using them to serve web pages for human readers, it extends them to share information in a way that can be read automatically by computers. This enables data from different sources to be connected and queried (Bizer et al., 2009). RDF triples of hazard class are presented in Table 7. This "way of thinking" enables a connection between all "information elements". Therefore, it is possible to create Linked Data of entire building regulations and more.

**Table 7: Structuring hazard classes in TEK10 §11 as RDF-triples**

| Relations – as basis for questions | | |
|---|---|---|
| *Start Node* | *Edge Label* | *End Node* |
| *Subject* | *Predicate* | *Object* |
| hazard_class | related_to | building_use |
| building_use | related_to | type_of_building |
| building_use | has | serious_hazard |
| building_use | has | permanent_users |
| users | heed | assistance |
| users | stay | overnight |

Figure 4 explains how the RDF can be implemented into software as XML. RDF can be regarded as a database for triples.

***Example: Hazard_class related_to building_use***

```
<rdf:RDF xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
  xmlns:tekrdf="http://www.example.org/">
  <rdf:Description rdf:about="http://dibk.no/hazard_class">
      <tekrdf:related_to>
        <rdf:Description rdf:about="http://dibk.no/building_use"/>
      </tekrdf:related_to>
  </rdf:Description>
…..
</rdf:RDF>
```

**Figure 4: XML-serialization of hazard class by use of RDF**

Figure 4 is an illustration for the concept, it and covers only the first triples of table 7. The "rdf:Description" must, of course, include all triples in this table by inserting this in the dotted line in the figure.

**Hazard classes presented as RDF-graphs.** Linked Data can also be presented as RDF-graphs. The graph is a collection of triples, referring to common resource(s). By the use of hyperbolic graphs, a large number of triples can be connected and visualized. Figure 4 included only one triple. However, this can easily be scaled up to represent the different types of building uses, presented in Tables 8 and 9.

World Wide Web Consortium (W3C) offers a free tool RDF/XML Validation Service (RDF-validator 2013) for validation of RDF triples. This net-based service accepts an RDF/XML document 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 was the "questions" structured, according to Table 8 and validated in the net, based by RDF-validator (2013).

**Table 8: Basis for development of RDF graphs about hazard classes**

| ***Subject*** | ***Predicate*** | ***Object*** |
|---|---|---|
| tekrdf:hazard_class | http://example.org/related_to | tekrdf:building_use |
| tekrdf:building_use | http://example.org/related_to | tekrdf:building_types |
| tekrdf:building_use | http://example.org/has | tekrdf:serious_hazard |
| tekrdf:building_use | http://example.org/has | tekrdf:permanent_users |
| tekrdf:users | http://example.org/need | tekrdf:assistance |
| tekrdf:users | http://example.org/stay | tekrdf:overnight |

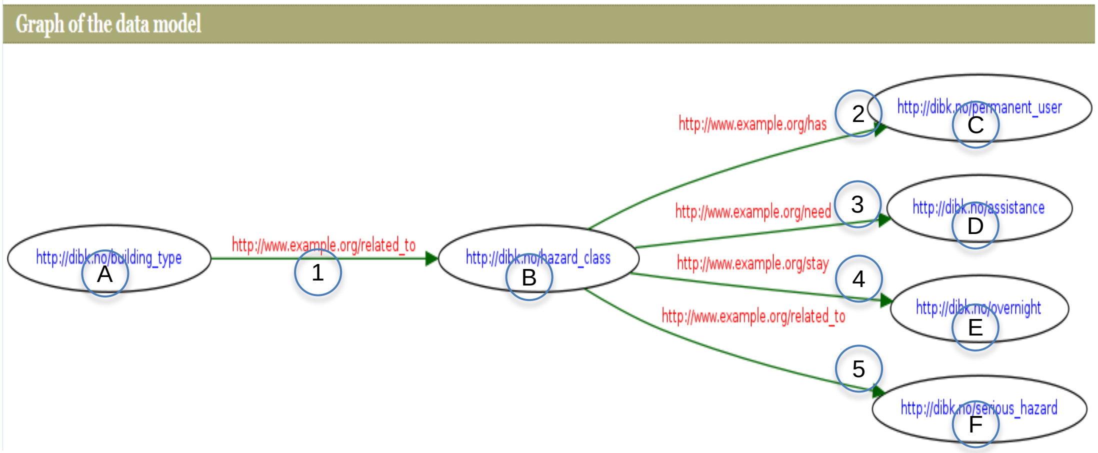
Table 9 is an automatic generated presentation of the triples done by the RDF-validator (2013). The inputs are the content in Table 8.

**Table 9: Validation of triples by RDF-validator (2013)**

**Triples of the Data Model**

| Number | Subject | Predicate | Object |
|---|---|---|---|
| 1 | http://dibk.no/building_type | http://www.example.org/related_to | http://dibk.no/hazard_class |
| 2 | http://dibk.no/hazard_class | http://www.example.org/has | http://dibk.no/permanent_user |
| 3 | http://dibk.no/hazard_class | http://www.example.org/need | http://dibk.no/assistance |
| 4 | http://dibk.no/hazard_class | http://www.example.org/stay | http://dibk.no/overnight |
| 5 | http://dibk.no/hazard_class | http://www.example.org/related_to | http://dibk.no/serious_hazard |

Figure 5 is automatic generated graph by the RDF-validator (2013) and is a presentation of the triples in Table 9. The font size of the text is hard to read, and the text is, therefore, presented separately below the graph. All nodes are linked, which prove that all data (nodes) are related to each other. The graphical presentation follows the logical structure (relation) of data and is independent of order in the XML-structure. Extending the network by adding more data and relations (Liked Data) is therefore applicable. The development of a network for information about building regulations from multiple sources should be applicable in practice.




| Nodes | Graphs |
|---|---|
| The pre http://dibk.no/ is identical for all nodes | The pre http://example.org/ is identical for all links |
| A) building type | 1) related_to |
| B) hazard class | 2) has |
| C) permanent user | 3) need |
| D) assistance | 4) stay |
| E) overnight | 5) related_to |
| F) serious hazard | |

**Figure 5: RDF graph of Hazard classes (RDF 2013)**

This concept illustrates the power of linked data. All terms used for determination of fire hazard class are linked together. If a completely new term is introduced, or as experienced during this study—the misspelling of a term—and if the RDF-validator is run, the result will be two separate graphs. This illustrates that the RDF-validator identifies which terms are linked and which are not in a very visual way.

The use of linked data is a semantic web approach. The number of nodes and graphs can in principle, be scaled up to unlimited size and be presented as hyper graphs (analog to hyperlinks for text). The use of RDF can be regarded as the last step of the 5-star data model, developed by Berners-Lee (2006). This step enables machine interpretable regulations and a semantic-based search for relevant information.

## EXTRACTING RELEVANT INFORMATION

**New ways of presenting regulations.** The use of liked data enables new approaches for identifying relevant information. The traditional way to figure out what is relevant information is to read all documents, word-by-word, to identify relevant parts. This principle is illustrated in Figure 6. The regulations can often be very difficult to understand, both related to the use of terms and to the structure of the regulations. Experiences from the "fire protection" case was that first, after reading the entire code and guideline, it was possible to know the impact that the small changes could have on the following parts.

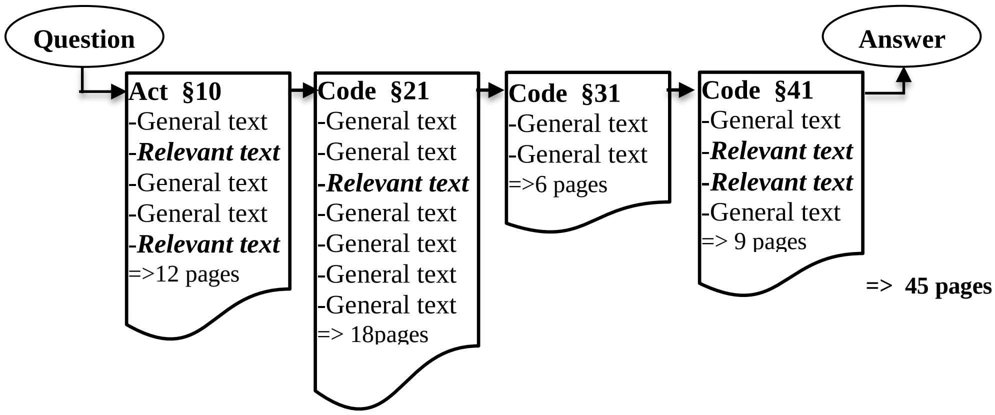



**Figure 6: Identifying relevant information by reading through**

Figure 7 illustrates the "Less is more" principle, by which the user only receives relevant information. An example of this can be: Give me a "print-out" of all relevant regulations for my project; one-floor garage at 50 m2, crest 5 meters, located 8 m from closest building. All of the sections in the regulation, which are linked to the constraints above, become identified and result in a "print out" of 5 pages. The answer can be supplemented with information (products or technical solutions) from other sources.

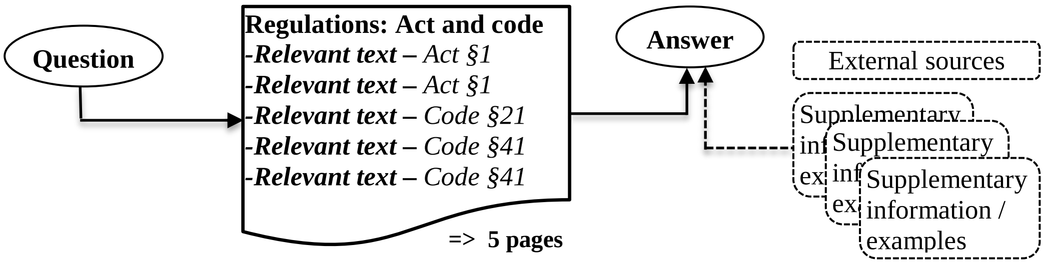



**Figure 7: Use of Linked Data, RDF, to extract relevant information**

The impact of this ontological approach for the identification of relevant regulations can be increased to focus on the development of machine readable and machine interpretable regulations. Users of regulations deal with digital ne-based solutions and not with the text version in the printing of the PDF format. The "Less is more" principle must be given priority, in relation to the attitude that if all documents are presented, then the authority has done a good job and cannot be criticized for a lack of information. The "lean-principles" from production are also relevant for the processing of information.

## IDENTIFYING RELEVANT REQUIREMENTS IN A SPECIFIC SITUATION BY USE OF DECISION TABLES

**Consequences of requirement in regulations.** Fire regulations do not typically stop a project, except when the cost becomes too high. The requirements can be fulfilled by re-designing or re-engineering or by adding relevant equipment. However, this can have a significant effect on cost, production time, and a number of other functions, layout, size of rooms, and of course, also on architecture. Therefore, it is important to have consequences in mind, when seeking solutions that have other benefits for the project. As an example, an extinguishing system can involve foam, dry chemicals, $CO_2$ or water mist, instead of a sprinkler. These options have different impacts on materials during and after a fire. The consequences can be more comprehensive than the fire. This can range from surface damages to the devastation of the structure. Table 10 presents a matrix, in which equipment is related to hazard class.

**Table 10: Equipment related to hazard class**

| **Hazard class** | | | | | | **Additional use / solutions** | **Required equipment / solution** | **Documentation in TEK10** |
|---|---|---|---|---|---|---|---|---|
| **1** | **2** | **3** | **4** | **5** | **6** | | | |
| | | | | | 6 | | Automatic fire extinguishing system | § 11-12 (part 1-b) |
| | | | 4 | | | Lift | Automatic fire extinguishing system | § 11-12 (part 1-a) |
| | 2 | 3 | 4 | 5 | 6 | | Fire alarm system | § 11-12 (part 2-a) |
| | | | | 5 | 6 | | Guideline system | § 11-12 (part 3) |
| | | | | 5 | 6 | Public use | Evacuation plan at entrance | § 11-12 (part 4) |

**Decision tables.** The use of decision tables is a precise yet compact way to model complicated logic. Decision tables—such as flowcharts and if-then-else and switch-case statements—associate conditions with actions to perform in a perspicuous way. A decision table provides a handy and compact way to represent complex business logic. In a decision table, the business logic is well-divided into: conditions, actions (decisions), and rules for representing the various components that form the business logic. Table 11 presents the framework of a four-quadrant decision table.

**Table 11: The four quadrants of a decision table**

| | |
|---|---|
| Conditions | Condition alternatives |
| Actions | Action entries |

This framework can be used for the requirements in Table 10. The output is presented in Table 12. For increased readability is all rules answered with No represented with “-“. Y is representing yes.

**Table 12: Decision table for equipment in variants of hazard classes**

| | Rules | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Condition alternatives** | | | | | | | | | |
| **Conditions** | Hazard class 1 | Y | - | - | - | - | - | - | - | - |
| | Hazard class 2 | - | Y | - | - | - | - | - | - | - |
| | Hazard class 3 | - | - | Y | - | - | - | - | - | - |
| | Hazard class 4 | - | - | - | Y | Y | - | - | - | - |
| | Hazard class 5 | - | - | - | - | - | Y | Y | - | - |
| | Hazard class 6 | - | - | - | - | - | - | - | Y | Y |
| | Lift | - | - | - | Y | - | - | - | - | - |
| | Public use | - | - | - | - | - | Y | - | Y | - |
| | **Action entries** | | | | | | | | | |
| **Actions** | Automatic fire extinguishing system | - | - | - | Y | - | - | - | Y | Y |
| | Fire alarm system | - | Y | Y | Y | Y | Y | Y | Y | Y |
| | Guideline system | - | - | - | - | - | Y | Y | Y | Y |
| | Evacuation plan at entrance | - | - | - | - | - | Y | - | Y | - |

Abbreviations: Y= Yes No = -

**Example of services.** The collaboration with the Norwegian Building Authority during this study has resulted in an increased awareness of the potential use of ontology engineering. However, this approach can be challenging to explain for a practitioner. The Norwegian Building Authority decided to develop a simple net-based application to demonstrate the potential of digital solutions in order to support the applicant and identify relevant information for his or her own project. This has resulted in the development of “Apply or nor apply?” (Søke eller ikke søke?) application illustrated in Figure 8.

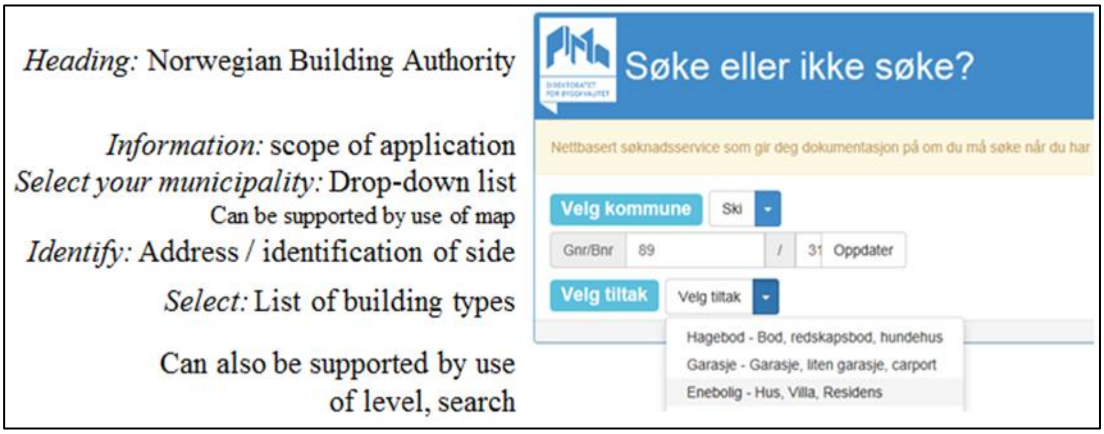



**Figure 8: Interface of “Apply or not apply” (DIBK 2014)**

This limited project was not meant to lead to the development of a new ontology engineering tool but to illustrate a practical solution, based on thinking ontology. The developed solution was due to time and funding, limited to a selection of most-used situations but can be scaled up without change of methods. The development of the decision tables was supported by use of question charts (Q-charts). Table 13 presents the content in the question charts.

**Table 13: Example of thesaurus for fire technical terms based on "height tool"**

| | |
|---|---|
| Question: | Which regulation is relevant for my building project? |
| Considerations: | List of elements like: Number of square meters, height, use of building, etc. |
| Exceptions: | Constraints in other regulations, like local site plans |
| Outcomes: | Relevant paragraphs |

This type of solution can be further extended into BIM-based model (BMC) solutions. The "rule complexity" is solved by the use of decision tables. The "facts complexity", related to considerations, can be retrieved from the content of information in the BIM file.

## PRINCIPLES FOR BIM-BASED MODEL CHECKING

**Support of BIM-based model checking.** Regulations are formulated for human interpretation, not for automatic processing in BIM-based model checking systems. The automatic processing of digital rules for trustworthy model checking are characterized by a clear logic, based on precisely specified information for the regulations. This, again, corresponds with a specified input of information from the BIM model. This requires a very transparent, clearly defined and detailed process, in addition to unambiguous information. Achieving this goal is not an easy task. This study indicates relatively simple ontology-based methods, which can be used to prepare regulations for digitalization.

BIM-based model checking relies on a consistent flow of information through the process. A common understanding of terms will support interoperability between terms in regulations, terms in the rules, and content of information in a BIM file in order to enable trustworthy compliance checking. This can be regarded as a 1-2-3 approach, based on following simplified steps that are illustrated in Table 14:

**Table 14: The 1-2-3 approach for development of BIM-based model checking**

| No. | Process | Aspect |
|---|---|---|
| 1) | Unambiguous terms and methodology | (Legal aspect) |
| 2) | Required information content of BIM model | (Construction aspect) |
| 3) | Software specification of the rule-set | (Informatics aspect) |

**Rule complexity versus facts complexity.** The impact of re-structuring the hazard classes, or type of buildings, is a significant simplification for the user. This approach illustrates the importance to distinguish between rule-complexity and facts-complexity. This situation is illustrated in Table 15 by using type of buildings.

**Table 15: Rule complexity versus facts complexity**

| **Type of complexity:** | | **Rule complexity** | |
|---|---|---|---|
| | | **Small** | **Large** |
| **Facts complexity** | **Small** | Garden shed | Biological laboratory |
| | **Large** | Combined housing | Airport |

Rule complexity relates to the requirement that is related to a building in a specific hazard class. This requires an overview of the regulations, but it is often easy to follow. Facts-complexity relates to criteria for being classified into one specific hazard class or type of building. The use of taxonomy with relevant questions is a very useful method. A reduction of facts-complexity must be processed in an efficient way, as presented in previous sections.

## DISCUSSION

This study presents the practical use of ontology-related methods and tools to support the interpretation of text. The outcome is presented by examples and proposals for practical use. The outcome should, therefore, be regarded as arguments and examples that ontology-based method and principles are applicable for the practitioner. This study intends to contribute with increased awareness of how ontology can be useful for the practitioners.

This study uses a limited number of methods and software and should, therefore, not be regarded as a ranking of methods or software. The software used in this study is available for free use. In this respect, the use of simple and existing methods and software tools been given priority, in relation to the development of specialized solutions. An underlying aspect in this study is that technology is not the problem. This must not be interpreted, as we have good software solutions. There is still a need for ontology engineering in the development of relevant methods and software.

## CONCLUSION

This study has explored methods and software, which can contribute to demystify the use of ontology-based methods and tools for interpreting text. The challenge has been to explore the practical use of methods and tools that are simple enough to be used by practitioners in the construction industry. This study indicates that the following methods can support this aim for increased understanding and consistent interpretations:

Terminology
- Use of Semantics of Business Vocabulary and Business Rules (SBVR)
- Develop definitions in a dynamic way

Shared vocabulary
- Linked data by use of Resource Description Framework (RDF)
- Searchable information

Restructuring of information
- Identification of relevant information
- Use of decision tables
- Foundation for BIM-based model checking (BMC)
- Principles for an increase of semantics by use of 5-star data model

The unclear and inconsistent use of terms and relations between terms has been identified, and examples for restructuring have been presented. The ontological approaches in this study have resulted in an alternative way of structuring regulations to prepare for the implementation of digital model-checking solutions.

The Norwegian Building Authority has been a partner during this study. This has resulted in the development of net-based applications for guidance of whether one needs to apply or not. This indicates that the development of small practical solutions for explaining the principles of ontological engineering is useful for gaining an increased interest for ontology. The use of explored methods has the potential to be part of the practitioners' toolbox for interpreting text in a consistent way.

## ACKNOWLEDGMENT

The author would like to thank the Norwegian Building Authority for sharing experiences and information. A special thank you for following up with the pilot project "Apply of not apply?", which resulted in a net-based solutions for guidance in the use of the regulations.

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