Computer-assisted Regulatory Compliance Checking

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ABSTRACT

The Architectural, Engineering, and Construction (AEC) domain, the fifth largest industry in New Zealand, has suffered from a decline in productivity over the years due to its highly diversified and fragmented nature, reluctance to adopt new technologies, and lack of interoperability. The emergence of BIM (Building Information Modelling) and the IFC (Industry Foundation Classes) data model specification in recent years has addressed some of these issues by providing an industry standard method to represent and exchange building information efficiently.

An incentive for BIM uptake in the AEC industry is the potential of automating regulatory compliance checking, which has traditionally been a manual process. Apart from the need to have a building representation, another key ingredient for this to happen is a digital representation of the regulations or standards. However, current regulatory texts are written for human interpretation and are poorly structured, which makes automation a challenge. In the absence of any official digital representation of regulations, researchers in the AEC industry have been proactively developing a range of interim solutions in the past four decades, and the quest for an ideal representation still continues today.

This paper examines the impact and applications of BIM in the industry, reviews common approaches in representing regulations for compliance checking, and also investigates the possibility and the advantages of adopting an open standard regulatory data exchange model as a way forward.

Categories and Subject Descriptors

I.2.1 [**Artificial Intelligence**]: Applications and Expert Systems – *law*; H.3.3 [**Information Storage and Retrieval**]: Information Search and Retrieval – *retrieval models*; D.2.12 [**Software Engineering**]: Interoperability - *Data Mapping*.

General Terms

Design, Legal Aspects, Experimentation, Performance

Keywords

BIM, Building Information Modelling, IFC, Industry Foundation Classes, Compliance Checking, Regulations, Legal Knowledge Representation, Open Standard Data Exchange

1. INTRODUCTION

The AEC industry is the fifth largest industry representing 8% of New Zealand's economy, but has suffered from declining productivity over recent years [18]. Research by Business and Economic Research Limited (BERL) in association with Building Research Association of New Zealand (BRANZ) and Price Waterhouse Coopers (PWC) has shown that a 10% change in efficiency in the construction sector would bring about a 1% change in GDP [19]. This means that a 1% gain in productivity is worth $300 million in annual GDP improvement [18]. This has been the motivation behind the government's recently established "Building & Construction Productivity Partnership" that aims to increase the productivity in the industry by 20% by 2020 [22]. One of the first undertakings in this initiative is the New Zealand national on-line consenting system, which could utilise computer-assisted compliance checking.

The traditional paper-based data exchange approach is generally still the accepted method of information sharing in the AEC domain. In particular, compliance checking has largely been a manual process that is labour intensive, error-prone and represents a costly duplication of effort as the process is effectively repeated throughout the whole building life-cycle, from design through to the official consent approval stages, construction and facility management.

For the past four decades, a major challenge in the industry has been the quest for suitably practical digital representations of both the building and the building codes or regulations for computer-assisted compliance checking [21]. The emergence of BIM and IFC to represent the building, and the availability of increased computing power is definitely a step forward in the direction of automating the compliance checking task. However, the quest for a building code representation still continues. The lack of research contribution from the legal domain until recently, and the complexity in representing regulatory texts as computable objects, are the main contributing factors for the slow progress.

2. BUILDINGS REPRESENTATION

A building is constructed of a large number of components. Each component may consist of multiple elements having different composite materials. The enormous amount of information necessary to describe even a simple building and the complexity in capturing each object's semantics has posed a challenge for computing techniques to solve.

Some modern structures have such complex shapes and type of construction that they are not easily representable as buildings in standard models and could not have been built without computers.

The types of information necessary to describe a building include structured objects and their relationships, formulae, constraints imposed by the applicable standards and regulations, conventions, and principles of physical properties [2].

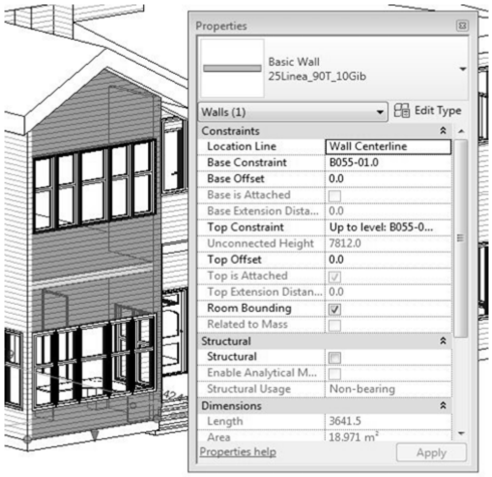

Figure 1: Example of a BIM object and properties

2.1 BIM

The traditional 2D CAD (Computer Aided Design) geometric representation systems used to document a building design have developed over the years into 3D representation systems through tools such as RUCAP, Sonata, REFLEX, ArchiCAD and AutoCAD, and recently shifted into a building information modelling (BIM) paradigm [10]. BIM is an object-based approach to design, construct and manage a building. It is also a digital representation of the entire building life cycle that allows interoperability (Figure 2). In a highly complex domain such as the AEC, the emergence of BIM technology is a major milestone towards a general productivity improvement. In particular, this would contribute towards the ability to automate some of the compliance checking tasks.

Commonly used BIM authoring tools in the industry include Revit, ArchiCAD, Bentley Architecture, Allplan Architecture, Vectorworks, and 4M Idea. An example of a BIM object with its properties in an authoring environment is shown in Figure 1.

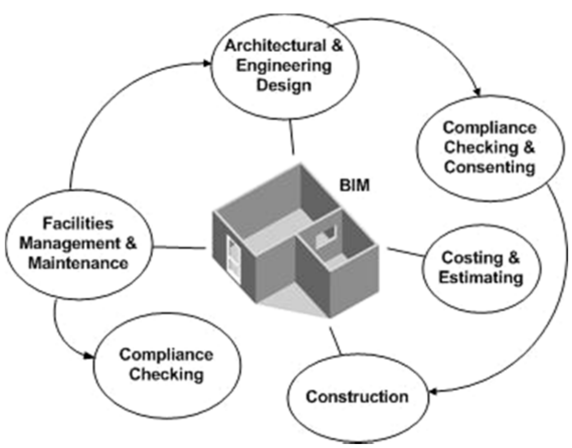

Figure 2: BIM Interoperability

2.2 IFC

BIM model data is currently exchanged using IFC, which is the AEC industry specific ISO standard object-based information model. IFC has been developed since 1996 by the International Alliance for Interoperability (IAI), now known as BuildingSMART International. The latest version of the specification is IFC4 (Table 1), which is currently being accepted as an International Standard ISO 16739 [16].

The IFC specification is written in EXPRESS (ISO 10303 Part 11), which is an open standard data modelling and definition language published in 1994 as part of ISO 10303 or STEP (Standard for Exchange of Product Data) to allow the representation and exchange of product manufacturing information. As an interesting comparison, the Unified Modelling Language (UML), which is an industry standard in software engineering, was first released in 1997 and only accepted as an international standard (ISO/IEC 19501) in 2005. The IFC model structure can be illustrated using the EXPRESS-G graphical annotation (see Figure 3).

The IFC4 data model has 764 entities (Table 1), which makes it a significantly large data model in comparison with others from different domains, e.g. the Ship Common Information Model (SCIM) data model for the US Navy Shipbuilding, which is based on STEP, has approximately 300 entities [20].

Table 1: IFC4 Data Model Summary

Types	Qty	Examples
Defined Types	126	ifcReal, ifcBoolean, ifcDate, ifcLengthMeasure, ifcDimensionCount, etc.
Enumeration Types	12	ifcBuildingSytemTypeEnum, ifcRoofTypeEnum, etc.
Select Types	59	ifcSpaceBoundarySelect, ifcUnit, ifcMeasureValue, etc.
Entities	764	ifcBuilding, ifcWall, ifcDoor, ifcWindow, ifcFurniture, etc
Functions	43	ifcDimensionsForSIUnit, ifcNoOfLayers, etc.
Rules	2	ifcRepresentationContextSameWCS, and ifcSingleProjectInstance
Property Sets	408	Pset_BuildingUse, Pset_SpaceCommon, etc.
Quantity Sets	91	Qto_BuildingStoreyBaseQuantities, Qto_WindowBaseQuantities, etc.
Individual Properties	1691	BarCode, BuildingHeightLimit, SpaceHumidity, etc.

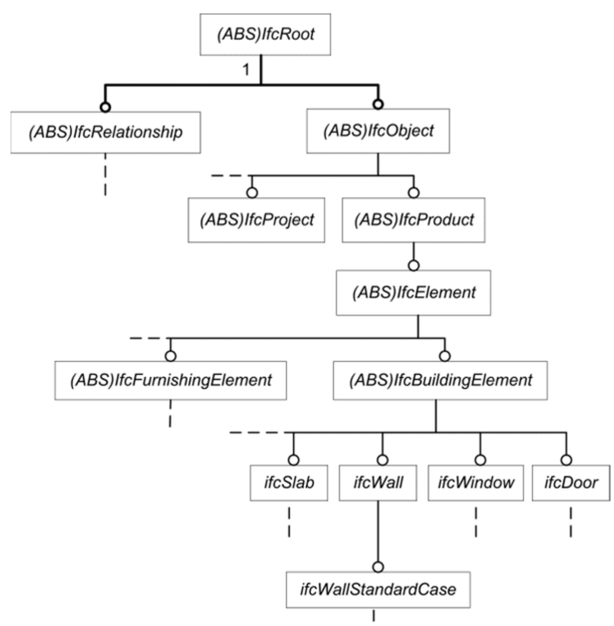

Figure 3: Part of the IFC model structure in EXPRESS-G

Using IFC, building information can be shared between architectural design applications and engineering or CFD simulations [8, 27]. Since its inception, IFC has gradually been adopted by the industry. Several European countries, such as Finland and Denmark, as well as Singapore have imposed the requirement to submit IFC-based building models as part of their online consenting.

It has taken 15 years to mature, but as it stands, IFC is a very significant object-oriented open standard data model that captures the semantics of the domain.

The IFC model data is usually exchanged as a STEP Physical File (SPF) using a clear text encoding defined by ISO 10303 Part 21 (STEP-File), i.e. ASCII format (see Figure 4). Alternatively, it can be exchanged using ifcXML as defined by ISO 10303 Part 28 (STEP-XML). Mapping between EXPRESS and a UML schema has also been made possible by ISO 10303 Part 25 since 2005.

```
ISO-10303-21;
HEADER;
 FILE_DESCRIPTION(('IFC2X_PLATFORM'),'2;1');
 FILE_NAME('TwoRoom2J','2006-09-09T21:58:26',(''),(''),'Autodesk Revit','20060505
 FILE_SCHEMA(('IFC2X2_FINAL'));
ENDSEC;
DATA;
  #1=IFCOWNERHISTORY(#3580,#1090,$,.NOCHANGE.,$,$,$,0);
  #2=IFCGEOMETRICREPRESENTATIONCONTEXT($,'Model',3,1.0E-6,#17,$);
  #3=IFCDIRECTION((0.0,0.0,1.0));
  #4=IFCCARTERSIANPOINT((0.0,0.0));
  #5=IFWALLSTANDARDCASE('2K3MuluD98deqAbRvz$6hO',#1,'Basic Wall: 10G100T1
  #6=IFCWALL('3bJsw0iyTEvAnNgH_nILK6',#1,'Basicl Wall:10G100T10G');

...

  #5090=IFCRELDEFINESBYPROPERTIES('2HuXPu$Rr2EBFBZzdjpXb1',#1,$,$,(#9,#7,#1
  #5091=IFCRELDEFINESBYPROPERTIES('02vY02FvH30f2d8ONM69BH',#1,$,$,(#9,#7,#
  #5092=IFCRELCONTAINEDINSPATIALSTRUCTURE('1mBWkNc_n26wOvL3xfpfN0',#1,
ENDSEC;
END-ISO-10303-21;
```

Figure 4: An excerpt of an IFC data model in SPF

3. REGULATIONS REPRESENTATION

Conventionally, design standards and building codes or regulations are written in natural language for human interpretation. Over the years, there have been numerous attempts to replicate regulatory texts as digital representations for computer processing. The most common approach to date has been rule-based systems, i.e. IF-THEN-ELSE rules or decision tables. Other approaches reported include the use of hypertext and hyper-document modelling [11, 28, 29], as well as the application of Natural Language Processing (NLP) and semantic modelling techniques to allow computers to interpret complex legal texts [25, 32].

Although there have been some successful implementations, the underlying challenge to represent regulatory texts digitally remains with the often poorly structured regulatory documents, as well as the ambiguity and inconsistency in the semantics of the regulatory contents. More importantly, the current manual practice of keeping an independent digital representation up to date with the frequently revised regulatory texts is a tedious and costly process.

3.1 Early Successful Code Representation

Historically, codes and standards in the AEC domain were mostly prescriptive and published as a set of procedures or rules. This allowed the development of knowledge-based systems that were successfully implemented throughout the 1970’s. One important early attempt was the implementation of decision tables in 1969 with the AISC (American Institute of Steel Construction) Specifications, which was used as a design tool in practice well into the 1980’s [12].

A simple example of a decision table is given in Table 2. In this example, four rules are being evaluated, as follows:

1. The number of occupants does not exceed 50 persons and an automatic fire alarm system is installed.
2. The number of occupants does not exceed 50 persons but there is no automatic fire alarm.
3. The number of occupants exceeds 50 persons and an automatic fire alarm system is installed.
4. The number of occupants exceeds 50 persons but there is no automatic fire alarm.

For each rule there is an applicable corresponding action, as follows:

1. A single egress path up to 20 m long is acceptable.
2. A single egress path up to 40 m long is acceptable.
3. At least 2 egress paths, each up to 20 m long is acceptable.
4. At least 2 egress paths, each up to 40 m long is acceptable.

Table 2: A Simplified Fire Egress Requirement

Conditions	**Rules**			
	1	**2**	**3**	**4**
Occupants <= 50 persons	Y	Y	N	N
Automatic fire alarm installed	Y	N	Y	N
Actions				
Max egress distance to exit = 20 m	x		x	
Max egress distance to exit = 40 m		x		x
Single egress path is OK	x	x		
Must have 2 or more egress paths			x	x

Notes: Y = Yes or True, N = No or False, x = applicable

The decision table logic approach lends itself well to a procedural standard such as the AISC Specifications. However, hard-coding rules, particularly a large complex network of decision tables, into a design tool soon became an issue as any revision to the regulatory content would require reprogramming and costly modifications.

In 1984, one of the most significant code representation systems developed, known as SASE (Standards Analysis, Synthesis and Expression), was released by the US National Bureau of Standards (now NIST). It was developed to assist with the formulation, promulgation and maintenance of a standard representation as a separate knowledge-base from the design tool [12, 17]. SASE was intended to provide a method to analyse and restructure existing standards, and to assist in developing new standards, with a focus on facilitating the creation of digital representations of the standards. This has contributed greatly to the improvement of the AISC specifications and other standards using the system.

3.2 Open Standard Legal Data Model

In the legal domain, there have been initiatives for open standard legal data exchange such as the XML-based standard Akoma Ntoso (Architecture for Knowledge-Oriented Management of African Normative Texts using Open Standards and Ontologies) [30], Norma-System [23] and CEN MetaLex [30], legal rules LKIF (Legal Knowledge Interchange Format), LegalRuleML [3], etc.

The Akoma Ntoso was started in 2004 by the United Nations (UN) to promote the interoperability of parliamentary, legislative and judiciary information across the Pan African Parliaments [30] (see Table 3 for the data model summary). CEN MetaLex started in 2006 to provide a standardised view of the European legal documents for interoperability via the internet. A recent effort to represent legal knowledge for applications in legal reasoning and the business rule domain has resulted in LegalRuleM [24], which is an extension of RuleML that was initiated around 2001 by an international consortium to represent all types of rules. Further work is currently being undertaken by OASIS (Advancement of Structured Information Standards) to standardise LegalRuleML.

There are also recent international efforts to encourage transparency and accessibility of legislative and governmental information with e-government web sites. These initiatives and the related work carried out by the OASIS will provide an interoperable data exchange platform that would potentially benefit the AEC industry.

Table 3: Akoma Ntoso Data Model Summary

Types	Qty	Examples
Attribute Group	33	actor, date, modifiers, link, period, etc.
Elements	289	act, amendment, application, domain, paragraph, workflow, etc
Element Group	40	amendmentBlock, collectionDocs, documentType, workProperties, etc ifcMeasureValue, etc.
Complex type	53	akomaNtosoType, basehierarchy, bodyType, containerType, etc
Simple type	17	eventType, language, statusType, versionType, yesnoType, etc.

At the same time, the development of semantic web technology by the World Wide Web Consortium (W3C), together with the emerging RDF (Resource Description Framework) and Web Ontology Language (OWL2) standards provide an efficient method of sharing digital legal knowledge representations. For example, CEN MetaLex can be exchanged using RDF. Some of the advantages foreseeable in using an open standard data model with semantic web technology would include the ability to automatically update the representation with regulatory amendments.

The scope provided by these open standard data models is currently limited to the representation of the texts and structure of legislation and legislative documents. However, the approach can potentially be extended to represent domain specific regulatory knowledge for compliance checking purposes.

In view of the general direction taken by legislative bodies and standards authorities in various jurisdictions around the world to adopt an open standard legal data exchange protocols, any attempt in the interim to represent standards and regulations for the purposes of computer-assisted compliance checking will certainly benefit from working with these protocols.

3.3 New Zealand Building Code (NZBC)

The NZBC is part of the Building Regulations made under the New Zealand Building Act 2004, which is New Zealand's official legislation. It is a performance-based code containing 35 technical clauses covering aspects such as fire safety, structural stability, health and safety, access, moisture control, durability, energy efficiency, and services and facilities.

A performance-based code does not prescribe how a design and construction process should be carried out, but each of the technical clauses specifies the functional requirements, and the qualitative or quantitative performance criteria to which the completed building and its components must meet throughout its intended life. This allows for innovation and uniqueness in designs proven by established scientific and engineering principles. Performance-based codes are usually accompanied by a set of prescriptive requirements, which are deemed to satisfy the performance criteria, to facilitate the compliance of common building designs.

NZBC allows two means of compliance, namely the "Acceptable Solution" (or deemed-to-satisfy solution), which demonstrates full compliance with the prescriptive requirements of the accompanying Compliance Documents, and the "Alternative Solution" by means of a proven engineering design, which usually involves calculations and/or simulations as well as external design reviews.

An example of a functional requirement, and quantitative as well as qualitative criteria of NZBC performance-based code relating to the protection from fire [7] is shown in Table 4. Terms shown in italics have special meanings, which are defined in a separate section of NZBC. In a computerised representation, these could be defined as part of a domain specific ontology.

Table 4: Functional Requirement and Performance Criteria

Functional Requirement	
C4.2	*Buildings* must be provided with means of escape to ensure that there is a low probability of occupants of those buildings being unreasonably delayed or impeded from moving to a *place of safety* and that those occupants will not suffer injury or illness as a result.
Performance – Quantitative Criteria	
C4.3	The *evacuation time* must allow occupants of a *building* to move to a *place of safety* in the event of a *fire* so that occupants are not exposed to any of the following: (a) a *fractional effective dose* of carbon monoxide greater than 0.3 (b) a *fractional effective dose* of thermal effects greater than 0.3 (c) conditions where, due to smoke obscuration, visibility is less than 10 m except in rooms of less than 100 sq m where visibility may fall to 5 m.
Performance – Qualitative Criteria	
C4.5	Means of escape to a *place of safety* in *buildings* must be designed and constructed with regard to the likelihood and consequence of failure of any *fire safety systems.*

4. COMPLIANCE CHECKING

AEC is a highly regulated domain. The design, construction, and maintenance of a building are all subject to compliance with a large number of regulations, codes and standards.

During the design phase of a building, a computer-assisted compliance checker can provide a quick audit against a set of conformance metrics for different aspects of the design. For the past 30 years, we have seen this kind of functionality built into a variety of dedicated building design tools, particularly in the engineering discipline. Current design tools incorporating compliance checking functionality include a wall bracing system design tool for conformance with the New Zealand Standard (NZS) 3604, a structural steel member engineering design tool for conformance with the AISC, etc. The regulatory requirements are usually represented as hard-coded rules in the tools making them unresponsive to any official amendment. A common approach in this type of compliance checking is to compare a trial calculation result with the quantitative criteria of the regulation or standard. The design process is usually repeated until compliance is achieved.

Computer-assisted compliance checkers would speed up the design approval process considerably as the complete design can be checked against all relevant regulations, codes and standards. A large scale compliance checking approach would compare each object or system in a building model with the constraints in a regulations representation. The output is usually a list of non-conformant objects.

Prescriptive regulations can usually be encoded into rules for checking purposes relatively easily. However, performance criteria, particularly those that are qualitative in nature, are much more complex to check against. One approach would be to specify a range of acceptable discrete values for each high level criterion. As a simplified example, the term “place of safety” (see Clause 4.5 in Table 4) can be defined more explicitly as follows:

1. Unconfined space outside the building, or
2. An enclosed space within the building that has the following attributes:
    a. The enclosure (walls, floor and ceiling) has a fire resistance rating of 60 minutes minimum, and
    b. At least two egress paths available that lead directly to the outside of the building, and
    c. The space is protected by an automatic fire sprinkler system.

Another approach would be to use the result of a simulation in conjunction with a set of metrics. For example, the simulated level of carbon monoxide concentration produced by a fire in a space can be checked against an acceptable threshold to determine if the space is considered “tenable” or safe.

For higher level qualitative criteria that cannot be resolved easily, a degree of human input may be required. For example, the criterion “*certain structural systems in buildings shall remain stable during and after fire*” would require a manual determination as to which structural systems are affected and what level of stability is acceptable.

4.1 Early Compliance Checkers

Following the success of SASE to assist in the creation of a regulations representation that can be maintained independently of the design tool, a number of compliance checking systems were developed to take advantage of this feature. SPECON (Specification Consultant) is a small expert system written in LISP for use with AISC. It was built on the backward chaining approach [26], which is a method of inference closely related to the actual intellectual process of compliance checking in practice. Another system is SICAD (Standards Interfaces in Computer Aided Design), which is a program written in FORTRAN that was successfully implemented as a design tool for the AASHTO (American Association of State Highway and Transportation Officials) Bridge Design System [17]. It is an executable rule-based system to query, navigate, evaluate and extract the required information from SASE-based decision trees. It would prompt the user for supplementary input where the information is not obtainable from the SASE database. SICAD has one limitation in that all information must be obtained in order for the compliance checking process to complete. SPEX (Standards Processing Expert) was developed in 1986 as a blackboard system utilising a SASE representation to determine conformance of component materials, structural and geometric properties with the design standards [6]. A few other compliance checking systems developed during this time include HI-RES, SPERIL, DURCON (Durable Concrete), WAVE, and SSPG (Stiffened Steel Plate Girder) [1].

4.2 Current Compliance Checkers

Since the emergence of the IFC open data model, there have been several commercial tools developed, namely Express Data Manager (EDM) Suite, now incorporating EDMmodelChecker, Solibri Model Checker (SMC), Fornax plan checking tool, Avolve plans review, Design Data System (DDS), and a few others.

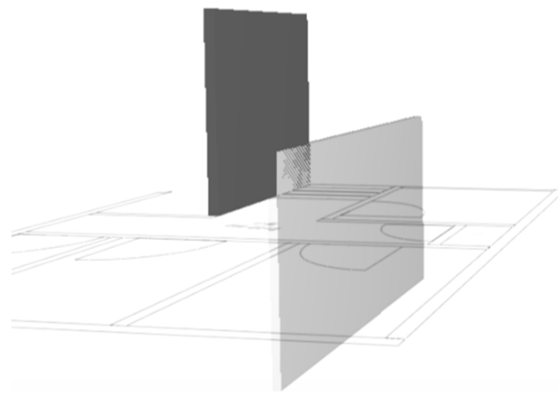

Figure 5: Example of object clash detection in SMC

Table 5: Example of a fire egress route analysis in SMC

Egress Analysis	Acc	Rej	Maj	Nor	Min
Fire compartment area must be within limits				x	
Fire walls must have correct wall, door, and window types				x	
Fire compartments must have spaces				x	
Model should have Stairs	x				
Model should have Exits	x				
Door minimum dimensions				x	
Spaces must be connected to doors	x				
If space is set to be Fire Exit Space, it has to have fire exit door				x	
Escape Route Analysis			x		

Notes: Acc = Accepted, Rej = Rejected, Maj = Major warnings, Nor = Normal warnings, Min = Minor warnings

While the EDM and Fornax tools are designed to be the components of larger systems, SMC is popular as a stand-alone Java-based visualisation rich compliance checking and reporting application. SMC was first released in 2000 in Finland and started out as a BIM model quality assurance and validation tool, e.g. for objects clash detection (see Figure 5). It has since developed into a more sophisticated rule-based design compliance checking system (see Table 5). SMC has a set of generic hard-coded rules with limited user-customisable parameters that is managed by the ruleset manager [9].

Despite having been identified as a bad practice in the past, SMC has hard-coded rules integrated into the tool, therefore new rules or major changes to existing rules can only be made by a SMC programmer.

There have been a few larger scale commercial implementation of compliance checking systems in the industry. This includes BCAider (1991-2005) in Australia [5], and ResCheck (Residential Compliance) and ComCheck (Commercial Compliance) in the US for checking against the energy standards (e.g. IECC and ASHRAE Standards 90.1), the GSA (General Service Administration) Courts Design Guide automation project [9], and Singapore's CORENET (Construction and Real Estate Network) system.

The CORENET system can be considered as the current most successful large-scale commercial implementation. It started out in 1991 from the Building Construction Authority (BCA) of Singapore as an electronic building consent submission system incorporating an in-house developed Building Plans (BP) Expert System to check 2D plans for compliance. The system was upgraded to CORENET e-Plan Check in 2002 replacing the 2D model representation with the IFC data model [4].

All the systems in use to date have incorporated hard-coded rules in proprietary formats to represent the applicable standards. Although some of these systems are managed by the government department that has control over any amendment to the standards [13], the representation would require frequent manual updates.

5. CURRENT RESEARCH

The research in this PhD sets out to investigate the application of open standard data models to represent regulations with examples from NZBC. In particular, Clauses C1 to C6 "Protection from Fire" of NZBC are being used in the case study. Both the prescriptive rules from selected sections of the Compliance Documents and the performance criteria need to be represented. Prescriptive requirements may be encoded into rules that can be used to query the building model, whereas performance criteria may be represented as a range of discrete values for validation by external calculations or simulations, in addition to some human input. Only a subset of the building model returned by each query as the model view definition (MVD) is to be checked.

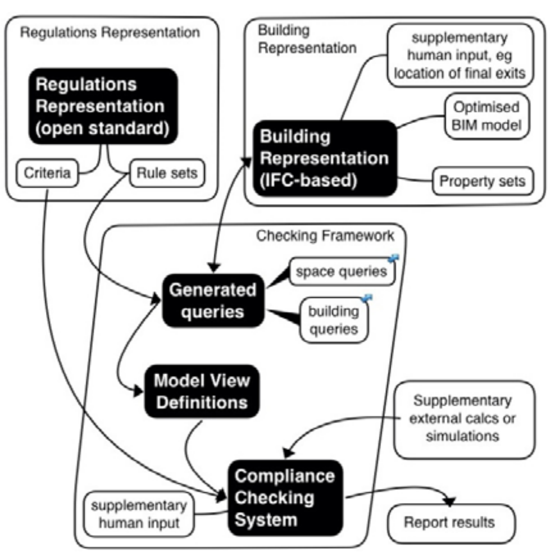

Figure 6: Automated Compliance Checking Process

A potential automated compliance checking process can be illustrated as shown in Figure 6. The research also examines the potentials of extending an open standard legal knowledge representation such as LegalRuleML or LKIF with the IFC data model for compliance checking in the semantic web environment. Adapting an open standard specification allows frequent regulatory amendments to be more easily assimilated into the representation without the need to recode it.

6. CONCLUSION

There has been significant research in the area of computer-assisted compliance checking for the AEC domain that deals with procedural standards and prescriptive regulations, because they tend to be easier to manage and code [31]. However, very few address the compliance checking against quantitative and qualitative criteria of the performance-based codes. Where research has examined performance-based codes, consideration was mainly given to the prescriptive parts of the codes [14, 15]. The current research attempts to fill this gap in the context of New Zealand's performance based codes.

All current compliance checking systems employ embedded rules that would require manual updates and regular maintenance in response to code changes. As legal knowledge is being converted into digital resources for interoperability by officials in the legal domain, adapting an open standard legal data model may alleviate the need to maintain yet another set of rules. For example, any working set of standards representation can be automatically updated with the revised standards as they are published online.

7. ACKNOWLEDGMENTS

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