Automated Building Code Compliance Checking – Where is it at?

Abstract

There has been an extensive amount of research conducted internationally over the last four decades in the area of automated and semi-automated regulatory compliance checking for the Architecture, Engineering, and Construction (AEC) industry. This paper summarises the earlier research initiatives, explores common themes and different approaches used, as well as comparing the strengths and limitations of a number of major code compliance checking tools. Some of these tools have been implemented commercially and others are beginning to be adopted or are in their final stages of development. The paper also examines how readily these tools can be applied in the context of a performance-based code as found in New Zealand.

Due to a recent push for innovation and productivity improvement in the AEC industry, there is an increased uptake of building information modelling (BIM) and the Industry Foundation Classes (IFC) open standard data model for interoperability. The availability of high performance personal computers, efficient web-based technology, and new initiatives in legal knowledge representation modelling should make the development of commercial compliance checking systems more viable than ever. However, the quest for an industry agreed unified approach seems to be far from over.

Research is being conducted to develop a computer interpretable representation of New Zealand's performance-based codes using an open standard legal data exchange protocol. This is to be integrated into a web-based BIM compliance checking framework. The fire safety clauses of the New Zealand Building Code (NZBC) are used in the case study.

Keywords: building information modelling (BIM), industry foundation classes (IFC), automated compliance checking, performance-based code, standards representation

Introduction

We live in a built environment designed around rules to ensure our safety and well-being. A building is subject to multiple regulatory compliance assessments throughout its entire life. As part of the design process, building designers ensure that every aspect of their design adheres to various regulatory requirements. The design is then subject to formal audit by the consent processing authority as part of the approval process. During construction and commissioning, every building component is checked before and after installation to ensure that the quality of products and workmanship conforms to the specified standards. The facility management of a building also requires regular compliance audits to ensure that the building is used and maintained as required and as designed. Even at the demolition stage, compliance checking is vital to ensure safety of occupants in the neighbouring buildings and to protect the surrounding environment during the work. In New Zealand, these codes are performance-based.

The conventional practice of code compliance checking in the industry has largely been a manual process, which is laborious, costly, and error prone. There have been numerous attempts over the last three decades to automate the process, but the progress has been slow. The fragmentation and diverse nature of the industry, complex network of stakeholders, competitiveness, declining productivity and a lack of motivation to adopt new technology have certainly contributed to this (El-Diraby and Kinawy, 2008; Froese et al., 2007; Masterspec - Construction Information Ltd, 2012).

The ability to share and interoperate pertinent information efficiently between the stakeholders in a building project (e.g. architects, engineers, project managers, construction contractors, building owners and local authority) is a key ingredient for an automated compliance checking system. The need for interoperability in the industry has long been identified (Gallaher et al., 2004; Halfawy et al., 2002), but it has remained as a challenge.

The cost of inadequate interoperability in the US capital facilities industry was quantified by NIST in 2004 to be US$15.8 billion annually (Gallaher et al., 2004). This is equivalent to approximately NZ$295 million annually for commercial and residential construction projects in New Zealand.

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. Also, as the industry makes up 8% of the economy a 1% gain in the productivity is worth NZ$300 million in annual GDP improvement (Nana, 2003). This has been a motivation for the recently established government's initiative "Building and Construction Productivity Partnership" that aims to increase the productivity in the industry by 20% by 2020 (Page and Curtis, 2012), which is a potential saving of about NZ$6 billion per annum (Masterspec - Construction Information Ltd, 2012). One of the first undertakings in this initiative is the New Zealand national on-line consenting system currently being developed, which could utilise a code compliance checking system.

1.1 Research Methodology

The techniques of Systematic Literature Review (SLR), or Systematic Review (SR), have been used to help identify the available primary studies relevant to this research topic. Borrowing the PIOC (Population, Intervention, Outcome, Context) criteria from the medical SR guidelines (Kitchenham and Charters, 2007), a search strategy was developed. Using these criteria with references gathered from several main primary studies, a set of keywords were derived for use in literature searches. A total of about 320 relevant references spanning across 40 years have been identified. Some of the more significant primary studies identified and their influences have been presented in a timeline (Figure 1). The development of personal computers, internet technology and CAD systems are plotted as a background reference.

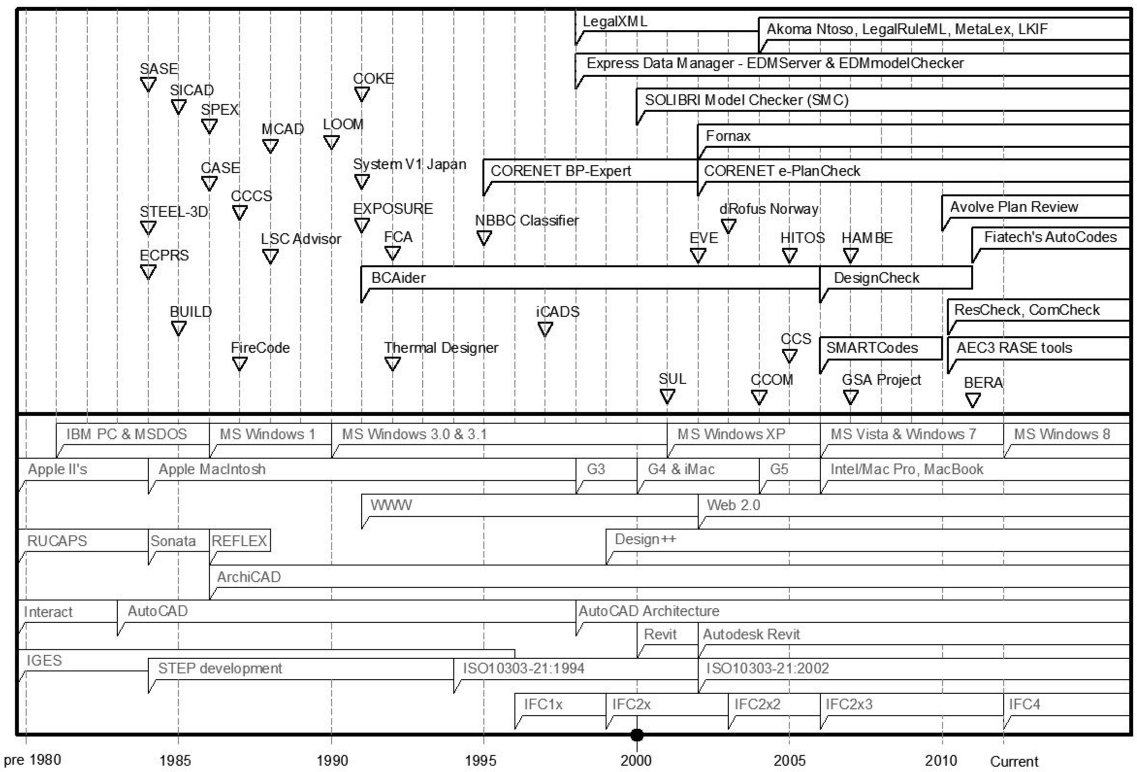

Figure 1: Timeline of International Research into Code Compliance Checking

Regulatory Framework for AEC industry in New Zealand

The regulatory framework for the AEC industry in New Zealand consists of the Building Act 2004, which is the official legislation; Building Regulations, which are made under the Act; and the NZBC, which is part of the Building Regulations (Merry and Spearpoint, 2008).

1.2 Compliance with NZBC

NZBC is a performance-based code and consists of two preliminary clauses and 35 technical clauses covering aspects such as fire safety, structural stability, health and safety, access, moisture control, durability, energy efficiency, services and facilities. Each technical clause specifies functional requirements as well as qualitative or quantitative performance criteria to which the completed building and its components must conform throughout its intended life. A performance-based code does not prescribe how a design and construction process should be carried out, but instead allows for innovation and uniqueness in designs, which must be proven by established scientific and engineering principles.

There are two ways to comply with the NZBC, namely the “Acceptable Solution” or deemed-to-satisfy solution, which shows full compliance with the relevant 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 an external design review process.

Automated Compliance Checking

A common approach to automated compliance checking is systematic comparison, i.e. comparing each object or system in a building model representation with the constraints in a standard. The output is usually a list of non-conformant objects.

A major challenge has been the quest for suitably practical digital representations of both the building and the standards (Nawari, 1987; Nawari, 2012). A few factors attributed to the slow progress have been the unavailability of an industry standard data model specification and the lack of computing power until recently. Another contributing factor is the complexity in representing regulatory texts as computable objects (Drogemuller et al., 2000; Moulin, 1992) and there has been little research contribution in this regard from the legal domain until recently.

Building Model Representation

CAD has been used to represent a building two dimensionally since the early 1960's. It has since developed into a 3D representation tool through systems such as RUCAP, Sonata, REFLEX, as well as ArchiCAD and AutoCAD, and now shifted into object-based Building Information Modelling (BIM) paradigm (Eastman et al., 2011).

The emergence of BIM technology and the IFC open data model specification for interoperability has provided a reasonable method and a generally agreed protocol for the digital representation of a building. IFC2x4, or IFC 4, is the latest model specification that is currently being accepted as International Standard ISO 16739 (Liebich, 2010).

Standards Representation

A considerable amount of energy has been invested by researchers into formulating an ideal digital representation of standards or regulations for use in compliance checking applications. Most of the research focused on encoding prescriptive regulations and their derivatives as rules in knowledge-based systems. One important early attempt was the implementation of decision tables in 1969 with the AISC (American Institute of Steel Construction) Specifications. The decision logic tables approach lends itself well to a procedural standard such as the AISC Specifications. This was implemented as a design tool for steel structures for at least 15 years (Fenves et al., 1969). Further work in this area resulted in the development of SASE (Standards Analysis, Synthesis and Expression) model by US National Bureau of Standards (now NIST) in 1984, which was one of the most significant early standards representation systems. SASE was implemented to manage the creation and maintenance of the decision tables and structure of the standards (Fenves et al., 1995; Lopez et al., 1989).

Throughout the 1980's, there is evidence of different approaches being investigated to computerise building regulations and standards in various parts of the world (Vanier, 1989). One approach was hyper-document modelling and the use of hypertext to represent regulatory provisions (Turk and Vanier, 1995; Vanier, 1989), which was the state of the art at the time. The concept of marking-up regulatory texts to create a computable representation has been revisited in a more recent work (Hjelseth and Nisbet, 2011; See, 2008).

Knowledge-based and expert systems were popular throughout the 1990's. They provided methods to encode regulatory information for use in design (Eastman et al., 2009; Frye et al., 1992; Mugridge et al., 1996; Rosenman and Gero, 1985), which is useful as long as the underlying knowledge-base is kept up to date with the current regulatory provisions. Despite the inherent inefficiency and the reliance on manual updates, the investigations into automated or semi-automated extraction of information from regulatory texts into rules and other computable objects have continued until today (Hjelseth, 2012; Kiyavitskaya et al., 2007; Zhang and El-Gohary, 2011, 2012).

A noted trend during the 1990's is the hard-coding of regulatory criteria into engineering design and analysis software suites (Fenves et al., 1995). This "black-box" approach of code representation has received a lot of criticism due to its non-transparency and inflexibility to regulatory changes. However, this practice has continued until today, although to a lesser extent, e.g. some hard-coded criteria are now provided with customisable parameters.

Creating an independent representation that derives data from legal sources maintained by a third party is far from ideal, unless it is linked to the source data and there is an automated update process in place. Otherwise, the representation would need to be manually amended or recreated to reflect the current status of the source documents, which are subject to on-going changes.

In the absence of an ideal digital representation of standards and regulations for the industry, the quest for a better interim solution continues. There have been projects using object-oriented and constraint-based approaches, as well as applying industry specific taxonomies and ontologies in combination with Artificial Intelligence (AI) and Natural Language Processing (NLP) techniques to allow machines to interpret regulatory texts (Cheng et al., 2008; Zhang and El-Gohary, 2011). Semantic modelling and the application of deontology, deontic logic, and Computational Law with NLP on an underlying domain ontology has also been explored (Salama and El-Gohary, 2011). A similar approach using Description Logic (DL) languages has also been investigated. This is based on a concept developed in the late 1970's (Hakim and Garrett, 1993) to allow for the automated description of engineering design knowledge as comparable objects. This concept was further improved with Typed Feature Structure (TFS) techniques by researchers in Australia (Woodbury et al., 2000).

Current regulatory texts are generally not written for machine interpretation and the effort put into making that a possibility by employing AI techniques has not been very successful so far. Furthermore, standards and building regulations often consist of complex multiple inter-related documents that are poorly structured and subject to frequent amendments, which is challenging for automation.

Provided that any standards representation can be linked to the source legal documents, AI and NLP techniques may provide a method of keeping the representation up-to-date by automatically capturing and incorporating the changes. However, an official data exchange protocol, that seems to be the current gap, would first need to be put in place. The International Code Council (ICC) that develops model codes in the US took an initiative and filled the gap by producing SMARTCodes in 2006 containing official representations of a few important standards. SMARTCodes provided the legislative body with an authoring tool to manage the amendments of the codes. Unfortunately, SMARTCodes development ended in 2010 due to a lack of funding. The underlying mark-up concept used by SMARTCodes has been developed further by AEC3 (UK) Ltd (Hjelseth, 2012). It is pertinent, however, that the application role remains with the legislative body, otherwise any representative standard created by the end user would require manual amendment every time the source information is updated.

Recently, there have been independent investigations undertaken by the legal domain in the field of legal informatics, legislation modelling and digital representation of regulations (Vitali and Zeni, 2007). These works are originally intended to facilitate the legislation process and providing easier public access to the legal resources, e.g. Crown Legislation Markup Language (CLML) of UK. However, recent work also includes some useful new initiatives in the legal data exchange protocol, e.g. MetaLex XML, Legal Knowledge Interchange Format (LKIF), and Architecture for Knowledge-Oriented Management of African Normative Texts using Open Standards and Ontologies (Akoma Ntoso), which is being standardised by the Organisation for the Advancement of Structured Information Standards (OASIS) as an open standard data model.

As indicated earlier, a computer interpretable standard representation should ideally be published and maintained by the government department responsible for producing the standards. The UN's e-Government initiative, which is being adopted around the world including New Zealand, provides a good platform for that purpose. In combination with the open standard legal data interchange initiatives and the work undertaken by OASIS, this may provide the solution the industry has been seeking for several decades.

Compliance Checking Applications pre-2000

This section reviews some of the early applications developed using the data representations discussed in the previous sections. The successful implementation of AISC Specifications in 1969 as a network of decision tables motivated a number of developments well into the 1980's. Examples include an advanced 3D graphical CAD system known as STEEL-3D for the design of steel frames to AISC Specifications (Pesquera et al., 1984), a software tool developed at Carnegie Mellon University for the design of reinforced concrete beams (Noland and Bedell, 1985), an automated compliance checking system developed at University of Austin (Jaeger and Harelik, 1985), and computerised building standards research at VTT Finland (Kähkönen and Björk, 1987).

Following the successful implementation of SASE, two compliance checking applications were developed. SICAD (Standards Interface for Computer Aided Design) incorporates one-way mapping functionality to assist the user to navigate, evaluate and extract required information from standards. Missing or incomplete data is managed by additional inputs from the user. This was implemented successfully as a design tool with AASHTO Bridge Design System and used for several years (Lopez et al., 1989). The Standards Processing Expert (SPEX) was another software application developed in 1986 based on SASE as a knowledge-based system to determine conformance of component materials, structural and geometric properties with the design standards (Delis and Delis, 1995).

The application of Artificial Intelligence (AI) techniques were explored by researchers in Australia in the mid 1980's. They came up with a prototype expert system called BUILD (Rosenman and Gero, 1985) as a proof of concept. Some of these techniques were later used in the development of BCAider and DesignCheck (Ding et al., 2006).

In New Zealand, research into the application of expert systems in this domain saw the development of FireCode in 1987, which was used to check design conformance with a draft prescriptive Fire Safety Code. Other related software applications developed included "Seismic" for checking building design against earthquake and wind loading requirements, WallBrace to assess compliance with light timber-framed building standards, an object-oriented system "ThermalDesigner" for checking conformance of a residential building with the Thermal Insulation Code in 1992, and the ALF spreadsheet tool for conformance checking with thermal insulation standards for residential buildings (Amor, 1992).

In the US, Life Safety Code (LSC) Advisor (1988), a rule-based compliance checking tool was developed for auditing architectural plans against the prescriptive requirements of LSC (known as NFPA 101) that regulates building design for life safety and fire protection. LSC Advisor was later extended and developed into an expert-system Fire Code Analyzer (FCA), at Massachusetts University around 1991. FCA is closely related to SICAD and uses a frame-based architectural model representation, a set of rules as well as some geometric algorithms (Delis and Delis, 1995). EXPOSURE, an expert system version of NFPA80a was also developed around this time for fire protection design of building exteriors (Smith, 1991).

iCADS (Intelligent Computer-assisted Design System) was another expert-system developed around 1990 with an extended knowledge-base covering space layout, structural system selection, day-lighting, artificial lighting, noise insulation, climate control and energy conservation, and construction costs. It incorporated a CAD system, a geometry interpreter, a relational database storing building and topological information, and an expert design advisor (Myers et al., 1992).

Compliance Checking Applications post-2000

Since the emergence of the IFC open data model, we have seen the development of several important tools that are being used today, namely Express Data Manager (EDM) Suite (now incorporating EDMmodelChecker), Solibri Model Checker (SMC), Fornax plan checking tool, Avolve plans review, Design Data System (DDS), etc.

In 1995, the Building Construction Authority (BCA) of Singapore initiated the CORENET (Construction and Real Estate Network) electronic consent submission system incorporating an in-house developed Building Plans (BP) Expert System to check 2D plans for compliance. The system was upgraded in 2002 to CORENET e-Plan Check replacing the 2D BP Expert System with the 3D IFC data model (Khemlani, 2005).

Express Data Manager (EDM) Suite was developed by Jotne EPM Technology in Norway in 1998 as an object database with tools to manage complex Product Data Models. It started out as a collaboration tool, but has since incorporated several additional modules including EDMmodelChecker that supports open development using the EXPRESS data modelling language (ISO 10303-11) (Yang, 2003).

Solibri Model Checker (SMC) was developed in Finland in 2000 and started out as a BIM model quality assurance and validation tool, but it has since developed into a stand-alone graphically-driven rule-based compliance checking and reporting application. SMC has a set of built-in rules that can be managed by a ruleset manager. A ruleset can be replicated, but the extent of user customisation is limited to changing parameters (Eastman et al., 2009).

BCAider was an expert system released in 1991 by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia. It was commercially available for compliance checking against the Building Code of Australia (BCA) until 2005. In 2006, CSIRO announced DesignCheck, a new system that incorporated EDM as the core rule bases and compliance checking engine for the BCA (Ding et al., 2006). DesignCheck has not been used commercially and there is no plan for further development.

The US Department of Energy produced and published ResCheck (Residential Compliance) and ComCheck (Commercial Compliance) to allow anyone to check a building design against the applicable energy standards, e.g. IECC and ASHRAE Standards 90.1. Both of these compliance checking applications have all the standards criteria hard-coded into the tools, although managed by the government department that have control over any amendment to the standards (Halverson et al., 2009). Similarly, the US GSA (General Service Administration) Courts Design Guide automation project also incorporates an independent ruleset manually derived from the textual standards (Eastman et al., 2009).

One of the latest efforts reported is the collaborated project between ICC, Solibri and Fiatech together with a few other software companies to develop AUTOCodes. This is currently a prototype system that promises an integrated compliance checking capability for the US building model codes (Fiatech, 2012).

An expert system of the nineties that has survived the test of time is Design++. It has been developed into a knowledge-based design automation tool in conjunction with BIM. Design++ has been incorporated into a number of commercial products including Bluethink's House Designer. Apart from giving advice to designers based on the evaluative rules, this system can also incorporate a set of generative rules for creating objects automatically (Huuskonen and Kaarela, 1995). Again, the rulesets are encapsulated into the application and can only be managed within the application.

All of the approaches discussed so far, including current commercial systems, appear to have one thing in common. They all use an independent standard representation either directly or via other dependent systems, and the representation is hard-coded into the system and is subject to manual updates by the software developers. For example, CORENET e-Plan is using the Fornax library in conjunction with EDM that has regulations and additional rules hard-coded in EXPRESS.

Performance-based Code Compliance Checking

In contrast to earlier approaches the development of a software tool is being investigated to assist with converting NZBC Clauses C1 to C6 “Protection from Fire” into a set of rules using one of the open standard legal data exchange formats such as MetaLex XML, LKIF or RuleML. Adopting an open standards specification allows revisions to be easily assimilated into an existing representation without the need to reconstruct it. Both the prescriptive requirements and quantitative performance criteria are to be represented in this way.

In the intended framework, the compliance checking component would read an IFC-based building model and audit the model against a selected set of open standard constraints. For clauses requiring subjective qualitative performance, the user can select a data exchange schema to allow the system to interact with external calculation or simulation modules. The returned result of the calculation can then be checked against the selected performance criteria either qualitatively or quantitatively.

Conclusion

Most of the research on automated compliance checking has focused on procedural standards and prescriptive regulations as they tend to be easier to manage and code (Yang and Li, 2001). Where research has examined performance-based codes, consideration was mainly given to the prescriptive parts of the codes (Han et al., 1998; Han et al., 2002; Hjelseth, 2012). Compliance checking against qualitative and quantitative performance criteria can be achieved semi-automatically using a combination of human input and data exchange with calculations or simulations modules. Unfortunately, there is little research in this particular area. The current research attempts to fill this gap in the context of New Zealand’s performance-based codes.

Based on the New Zealand National BIM Survey 2012, there is a strong trend of rapid uptake of BIM in the industry. However, there is a noted lack of agreed industry-wide protocols, tools and frameworks for interoperability (Masterspec - Construction Information Ltd, 2012). The initiative taken by the ICC with SMARTCodes and AUTOCodes is a positive step in this direction, but these systems still employ embedded rules that would require manual updates and maintenance in response to codes changes. As legal knowledge is being converted into digital resources for interoperability by officials in the legal domain, adopting an open standard legal data model may alleviate the need to maintain yet another set of rules. Revisions of standards can simply be imported into the system as an update to existing representations. In view of the general direction taken by standards authorities in various jurisdictions around the world to adopt a standard legal data exchange protocol, any attempt in the interim to represent standards and regulations for the purposes of computer-assisted compliance checking may benefit from investing in an open standard protocol offered by the legal domain such as those currently being developed at OASIS.

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List of Acronyms

AEC: Architecture, Engineering, and Construction

AI: Artificial Intelligence

AISC: American Institute of Steel Construction

Akoma Ntoso: African Normative Texts using Open Standards and Ontologies

BCA of Singapore: Building Construction Authority of Singapore

BERL: Business and Economic Research Limited

BIM: Building Information Modelling

BP Expert System: Building Plans Expert System

CAD: Computer Aided Design/Draughting

CLML: Crown Legislation Markup Language

ComCheck: Commercial Compliance Checker

CORENET: Construction and Real Estate Network

CSIRO: Commonwealth Scientific and Industrial Research Organisation

DDS: Design Data System

DL: Description Logic

EDM: Express Data Manager

FCA: Fire Code Analyzer

GDP: Gross Domestic Products

GSA: General Service Administration

iCADS: Intelligent Computer-assisted Design System

ICC: International Code Council

IFC: Industry Foundation Classes

LKIF: Legal Knowledge Interchange Format

LSC: Life Safety Code

NIST: US National Institute of Standards and Technology

NLP: Natural Language Processing

NZBC: New Zealand Building Code

OASIS: Organisation for the Advancement of Structured Information Standards

PIOC: Population, Intervention, Outcome, Context

PWC: Price Waterhouse Coopers

ResCheck: Residential Compliance Checker

SASE: Standards Analysis, Synthesis and Expression

SICAD: Standards Interface for Computer Aided Design

SLR: Systematic Literature Review

SMC: Solibri Model Checker

SPEX: Standards Processing Expert

SR: Systematic Review

TFS: Typed Feature Structure

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