# AN AUTOMATED BUILDING INFORMATION MODELLING-BASED COMPLIANCE CHECKING SYSTEM FOR MALAYSIAN BUILDING BY-LAWS FIRE REGULATIONS

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# DEDICATION

To Abah and Mama.
If oceans were ink, they would be exhausted, to write just how much you have supported me in this journey.

To Allahyarham Cikgu Hamzah bin Ahmad.
You showed me the courage of stars, how its light carries on endlessly even after its existence.

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# ABSTRACT

The implementation of Building Information Modelling (BIM) in the Architecture, Engineering and Construction (AEC) industry has significantly amplified the responsibility of designers in creating reliable and accurate BIM models. Fundamentally, the BIM models must comply with the fire safety regulations to provide minimum protection for building occupants and property. Since fire safety regulations are known to be complex and rigid, the manual compliance checking process could lead to inaccuracies, especially in a BIM-based environment. Hence, this study developed an automated BIM-based fire regulations compliance checking system for Malaysian's AEC industry. In order to establish the rules and BIM properties necessary for fire regulations compliance checking process, 256 clauses from Parts VII and VIII of Selangor Uniform Building (Amendment) (No. 2) By-Laws 2012 were selected to create a BIM model using Revit® based on two-dimensional drawings of a completed 17-storey institutional building. Three investigations were conducted to structure the representation of the rules and BIM properties. First, the fire safety clauses were formalised through a classification technique, semantic mark-up requirement, applicability, selection, exception (RASE) methodology, and interviewing two fire engineers and a representative from the Fire and Rescue Department Malaysia (JBPM). Secondly, the BIM properties consisting of 54 families and their respective parameters in Revit® were identified for the compliance checking process. Lastly, pseudocodes and architecture of the automated system were developed to establish the relationship between the formalised clauses and BIM properties. Dynamo® scripts were used to develop a prototype of an automated fire regulations compliance checking system which could automatically check for fire doors and staircases in Revit®. The representative from JBPM, three fire engineers and architect validated the proposed architecture while the prototype was validated by three architects, two structural engineers, one mechanical engineer, and two civil engineers. This study contributed to a semi-automated rule translation process which combined existing approaches in this field of study. The classification technique and semantic mark-up RASE methodology were refined in this research by developing flowcharts to provide specific guidelines in formalising the clauses. The semi-automated rule translation process encouraged the participation of relevant fire safety experts and provided more accessibility for designers compared to existing studies. This study also offered more practicality for designers to employ the system by utilising native BIM model data representation. High mean scores ranging from 4.00 to 4.96 were obtained for the validation process, which affirmed the feasibility of an automated BIM-based fire regulations compliance checking system to assist designers in the Malaysian AEC industry.

# ABSTRAK

Pelaksanaan pemodelan maklumat bangunan (BIM) dalam industri Senibina, Kejuruteraan dan Pembinaan (AEC) telah memperluaskan lagi tanggungjawab para pereka untuk mencipta model BIM yang tepat dan boleh dipercayai. Secara asasnya, model BIM perlu mematuhi peraturan keselamatan kebakaran bagi memberikan perlindungan minimum kepada sesuatu hartanah dan penghuni bangunan. Peraturan keselamatan kebakaran yang ketat dan rumit boleh menyebabkan berlakunya ketidaktepatan dalam proses pemeriksaan kepatuhan manual, terutamanya dalam persekitaran yang berasaskan BIM. Justeru, kajian ini dijalankan untuk membina sistem pemeriksaan kepatuhan peraturan kebakaran berasaskan BIM secara automatik dalam industri AEC di Malaysia. Bagi penetapan peraturan dan ciri-ciri BIM yang penting dalam proses pemeriksaan kepatuhan peraturan kebakaran, 256 klausa daripada Bahagian VII dan VIII Undang-Undang Kecil Bangunan Seragam Selangor (Pindaan) (Bil. 2) 2012 telah dipilih untuk mencipta model BIM menggunakan perisian Revit® berdasarkan lakaran dua dimensi bangunan institusi 17 tingkat yang telah siap dibina. Tiga peringkat penyelidikan telah dilakukan untuk menyusun gambaran peraturan dan ciri-ciri BIM. Pertama, klausa keselamatan kebakaran diformalkan melalui teknik pengelasan, kaedah keperluan, kebolehlaksanaan, pemilihan dan pengecualian (RASE) penanda semantik, dan sesi temubual bersama dua orang jurutera kebakaran dan wakil daripada Jabatan Bomba dan Penyelamat Malaysia (JPBM). Kedua, ciri-ciri BIM yang terdiri daripada 54 buah keluarga dan parameter masing-masing dalam Revit® telah dikenal pasti bagi tujuan proses pemeriksaan kepatuhan. Akhir sekali, pseudokod dan seni bina sistem automatik ini dibina untuk menjalinkan hubungan di antara klausa formal dan ciri-ciri BIM. Skrip Dynamo® digunakan untuk membina prototaip sistem pemeriksaan kepatuhan peraturan kebakaran ini, di mana pintu dan tangga kebakaran dapat diperiksa secara automatik melalui Revit®. Seorang wakil daripada JPBM, tiga orang jurutera kebakaran dan seorang arkitek mengesahkan cadangan seni bina ini, manakala tiga orang arkitek, dua orang jurutera struktur, seorang jurutera mekanikal, dan dua orang jurutera awam mengesahkan prototaip yang dibina. Kajian ini menyumbang kepada proses terjemahan peraturan separa automatik yang menggabungkan pendekatan sedia ada dalam bidang kajian ini. Teknik pengelasan dan kaedah RASE penanda semantik telah ditambah baik dalam kajian ini melalui penyediaan carta alir sebagai garis panduan khusus bagi proses pemformalan klausa. Proses terjemahan peraturan separa automatik ini turut menggalakkan penyertaan pakar keselamatan kebakaran yang relevan, selain daripada memberikan lebih banyak akses kepada para pereka berbanding kajian terdahulu. Kajian ini juga menawarkan lebih banyak peluang secara praktikal kepada para pereka dalam menggunakan sistem menerusi gambaran data model BIM asal. Proses pengesahan kajian ini menunjukkan skor min yang tinggi iaitu di antara 4.00 hingga 4.96, di mana ia membuktikan kebolehlaksanaan sistem pemeriksaan kepatuhan peraturan kebakaran berasaskan BIM secara automatik ini bagi membantu para pereka dalam industri AEC di Malaysia.

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| | | |
|---|---|---|
| ABM | - | Agent-based modelling |
| ACCBEP | - | Automated Code Checker of Building Envelope Performance |
| ACEM | - | Association of Consulting Engineers Malaysia |
| ADAAG | - | Americans with Disabilities Act Accessibility Guidelines |
| AEC | - | Architecture, Engineering and Construction |
| API | - | Application Programming Interface |
| AS | - | Australian Standards |
| BCA | - | Building and Construction Industry |
| BCF | - | BIM Collaboration Format |
| BCM | - | Building compliance model |
| BERA | - | Building Environment Rule and Analysis |
| BIM | - | Building Information Modelling |
| BIMRL | - | Building Information Modelling Rule Language |
| BREEAM | - | Building Research Establishment Environmental Assessment Method |
| BS | - | British Standards |
| bSDD | - | buildingSMART Data Dictionary |
| CAD | - | Computer-aided design |
| CCC | - | Certificate of Completion and Compliance |
| CCCS | - | Construction Code Consultation System |
| CCS | - | Cuneco Classification System |
| CDP | - | Compliant design procedure |
| CFD | - | Computational Fluid Dynamics |
| CIDB | - | Construction Industry Development Board |
| CORENET | - | Construction and Real Estate Network |
| CPIC | - | Construction Project Information Committee |
| CSC | - | Construction Specifications Canada |
| CSH | - | Code for Sustainable Homes |
| CSI | - | Construction Specifications Institute |
| DBK | - | Dansk Bygge Klassifikation |

| | | |
|---|---|---|
| D.G.F.R. | - | Director General of Fire and Rescue Malaysia |
| DSR | - | Design Science Research |
| EBC | - | Extended Building Code |
| EBIM | - | Extended Building Information Model |
| EDM™ | - | Express Data Manager |
| EPIC | - | Electronic Product Information Cooperation |
| FCA | - | Fire Code Analyzer |
| FCC | - | Fire Codes Checker |
| FOL | - | First Order Logic |
| FRP | - | Fire resistance period |
| GSA | - | General Services Administration |
| HVAC | - | Heating, ventilation and air conditioning |
| IAI | - | International Alliance for Interoperability |
| IBC | - | International Building Code |
| ICADS | - | Intelligent Computer Aided Design System |
| ICC | - | International Code Council |
| ICT | - | Information and communication technology |
| IDM | - | Information Delivery Manual |
| IE | - | Information extraction |
| IECC | - | International Energy Conservation Code |
| IEM | - | Institution of Engineers Malaysia |
| IFC | - | Industry Foundation Classes |
| IFD | - | International Framework for Dictionary |
| IFEM | - | Institution Fire Engineers Malaysia Branch |
| IR | - | Information retrieval |
| ISO | - | International Organization for Standardization |
| ITr | - | Information transformation |
| JBPM | - | Fire and Rescue Department Malaysia |
| KB | - | Knowledge Base |
| KBVL | - | KBim Visual Language |
| KPKT | - | Ministry of Housing and Local Government |
| ML | - | Machine learning |
| MS | - | Malaysian Standards |

| | | |
|---|---|---|
| MVD | - | Model View Definition |
| NBS | - | National Building Specification |
| NFPA | - | National Fire Protection Association |
| NLP | - | Natural Language Processing |
| LSC | - | Life Safety Codes |
| OSC | - | One-Stop-Centre |
| OWL | - | Web Ontology Language |
| PAM | - | Pertubuhan Akitek Malaysia |
| PAS | - | Predicate-argument-structure |
| POS | - | Part-of-speech |
| PWD | - | Public Works Department |
| RASE | - | 'Requirement', 'Applicability', 'Selection' and 'Exception' Methodology |
| RDF | - | Resource Description Framework |
| RIBA | - | Royal Institute of British Architects |
| RKM | - | Regulatory knowledge model |
| ROI | - | Return on Investment |
| SASE | - | Standards, Analysis, Synthesis, and Expression |
| SMC™ | - | Solibri Model Checker |
| SNACC | - | Semantic natural language processing-based automated compliance checking |
| SPEX | - | Standards Processing Expert |
| SQL | - | Structured Query Language |
| STEP | - | Standard for the Exchange of Product Model Data |
| SWRL | - | Semantic Web Rule Language |
| TC | - | Text Classification |
| TRA | - | Transformation Reasoning Algorithm |
| UBBL 1984 | - | Uniform Building By-Laws 1984 |
| VCCL | - | Visual Code Checking Language |
| VPL | - | Visual programming language |
| W3C | - | World Wide Web Consortium |
| WWW | - | World Wide Web |
| XML | - | Extensible Markup Language |

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# CHAPTER 1

# INTRODUCTION

## 1.1 Introduction

The Architecture, Engineering and Construction (AEC) industry is progressively changing through the emergence of Building Information Modelling (BIM). BIM is defined as "a modelling technology and associated set of processes to produce, communicate and analyse building models" (Eastman et al., 2018, p. 14). The extensive application of BIM in construction projects magnifies the urgency for the automation of various construction processes and the creation of well-defined information to be used throughout the project lifecycle. BIM provides a comprehensive framework for information handling and exchange by having high capability to store huge amount of information in BIM models (Zhong et al., 2018).

The evolution of BIM technology and issues pertaining to fire and building safety stimulate a wide development of studies in automating the code compliance checking process. Automated code compliance checking process is a computer-programmed analysis on the compliance of building designs based on the models' objects, attributes and relations (Eastman et al., 2009). The automated system extracts and translates building regulations into a computable format, generates an execution plan, checks the BIM models and lastly, produces a compliance result (Nawari, 2018). It promotes accuracy, consistency, comprehensiveness, and systemisation.

## 1.2 Background issues

The design phase is the primary component in AEC projects which influence other construction and management processes. The implementation of BIM technology raises the bar for the AEC industry to provide better building designs which are equipped with significant amount of information. The following subsections present an overview of the design considerations in BIM-based environment and the importance of fire safety regulations in the design phase. Accordingly, this leads to an overview of the current situation in improving the code compliance checking process for building designs in the AEC industry.

### 1.2.1 BIM-integrated design process

A typical development project consists of pre-development phase, construction phase, and post-construction phase (Abdullah, Harun and Rahman, 2011). This could be further defined into eight stages as outlined by the Royal Institute of British Architects (RIBA, 2020), which are, strategic definition (Stage 0), preparation and briefing (Stage 1), concept design (Stage 2), spatial coordination (Stage 3), technical design (Stage 4), manufacturing and construction (Stage 5), handover (Stage 6), and use (Stage 7). The spatial coordination activity in Stage 3 specifically deals with the coordination between architectural design and engineering design. This stage is included in RIBA Plan of Work 2020 to accommodate the technological evolution of design and construction processes through the application of BIM.

BIM elevates the building designs to be equipped with comprehensive information which could be utilised throughout the whole project lifecycle from the initial design phase until facility management (NIBS, 2015). BIM-related studies have thrived expeditiously over the last two decades in which recent studies focused more on the adoption of BIM in specific domains compared to the general conceptualisation of BIM in the early 2000s (Tang et al., 2019; Eastman et al., 2018; Santos, Costa and Grilo, 2017). The implementation of BIM has encouraged the development of various software applications (BIMForum, 2020). Examples of BIM design authoring software applications are Revit® (Autodesk, 2020e), ArchiCAD® (Graphisoft, 2020d), MicroStation® (Bentley, 2020d), Allplan® (Allplan, 2020g), and Tekla Structures® (Trimble, 2020b). BIM software applications are relatively more advantageous than computer-aided design (CAD) software applications due to the ability to create parametric elements that could automatically define the relationships and constraints of parameters in building objects, or also known as parametric modelling (Ahankoob, Abbasnejad and Wong, 2020; Eastman et al., 2018; Lee, Sacks and Eastman, 2006). The implementation of BIM in construction projects promotes better collaborative working environment among project participants through seamless data integration and exchange (Eastman et al., 2018; MHC, 2014).

Consequently, the ability to create a comprehensive, accurate and reliable set of information in BIM models has become the main priority in BIM-based projects (Pärn, Edwards and Sing, 2017). Thus, the design stage plays an important role in influencing the accuracy and reliability of information created. Essentially, this information must correspond to the client's requirement and comply to relevant building regulations (RIBA, 2020; Ching and Eckler, 2013; Imrie and Street, 2011; Pressman, 2012; Tunstall, 2006; Bownass, 2001). The building regulations, particularly the fire safety regulations are considered as a fundamental part of design process (Imrie, 2007).

### 1.2.2 Fire safety regulations in design process

The practicability of fire protection solutions according to relevant fire safety regulations is addressed as early as in the feasibility studies (RIBA, 2020; Bownass, 2001). As a whole, fire safety regulations were written by regulatory experts to protect the life of building occupants and property as well as to continue the operation of fire protection system during a fire incident (Stein et al., 2006; Lataille, 2003; Watts, 2003). The regulations contain passive measures which include the design of building elements and spaces, and active measures which involve the design of fire protection systems in building (Lataille, 2003; Bownass, 2001). The overall design process is governed by fire safety regulations that assert the minimum requirements for buildings to prevent fire occurrences and also to reduce fire growth rate in the event of fire (IFEM et al., 2006; Cote and Grant, 2003; Janssens, 2003; Friedman, 2003). Accordingly, each country and even state has its own set of fire safety regulations to be adhered to by designers.

In Malaysia, Uniform Building By-Laws 1984 (UBBL 1984), one of the by-laws enacted under Act 133, Street, Drainage and Building Act 1974, is the main reference for fire safety regulations. Each State Government has the authority to publish its own government gazette based on UBBL 1984 (MPC, 2016). For instance, Selangor Uniform Building (Amendment) (No. 2) By-Laws 2012 was produced by Selangor Government. All building designs are required to adhere to UBBL 1984 or any other related gazette versions of UBBL 1984 for development plan approval prior to the commencement of construction works (Aloysius, 2019; Abdullah et al., 2011). The Fire and Rescue Department Malaysia (JBPM) is responsible in reviewing and approving the compliance of building designs with the fire safety requirements (KPKT, 2019).

Building plan approval process is an essential constituent of the pre-development process. As stipulated in Circular No. 009 (BEM and BAM, 2020) and subsection 2 (a) of Architects Act 1967 (LAM, 2015a), architects and engineers are obliged to submit their respective building plans to relevant local authority in Malaysia. The current compliance checking process conducted by JBPM is bounded by a set of checklists in which the applicants, consisting of architects and engineers, are required to prepare the relevant calculations, building plans, and mechanical and electrical plans (JBPM, 2020b; KPKT, 2019). It is presumed that designers are well-versed with the fire safety regulations, and in the circumstances where there are design alternatives other than the minimum requirements, designers are obliged to recommend the solutions to JBPM (Aloysius, 2019). Thus, this shows that although JBPM has the highest authority to approve building designs, the technical competency to conduct a comprehensive compliance checking among designers is much higher compared to JBPM. For this reason, designers carry the utmost responsibility to ensure the optimum fire safety level in a building (Ramli, 2011; Imrie et al., 2011).

Architects are primarily aware that the fire safety regulations are the critical contributor in their designs and must be integrated at the earliest design stage. However, there are architects with an opposing view where they perceive regulations as a fixed constraint and a barrier to the creative process (Imrie, 2007; Maluk, Woodrow and Torero, 2017). Irrespective of their perceptions, fire safety strategy should be incorporated into every design stage (RIBA, 2020). The passive measures in fire safety strategy aim to prevent initial fire growth and also decrease the fire spread rate during fire occurrences (Cote et al., 2003). In the fire safety regulations, the passive measures are reflected in the requirements for fire resistance building materials, compartmentation, and evacuation-related building spaces (Tewarson, Chin and Shuford, 2003; Isa and Kamaruzzaman, 2012; Janssens, 2003; IFEM et al., 2006; Yatim, 2016a). On the other hand, the active measures aim to stimulate the awareness of occupants in the event of fire and provide an effective smoke management system in a building (Stein et al., 2006; Lataille, 2003; Ramli, 2011). The fire safety regulations specify the minimum requirements for fire detection, fire alarm, and fire extinguishment systems as well as the continuity of the systems' operations during fire occurrences (Stein et al., 2006).

However, the incorporation of minimum fire safety requirements in the design process could lead to an ambiguous procedure. Fire safety regulations are known to be subjectively complex and difficult to be interpreted (Malsane et al., 2015; Smith, 1991). The manual code compliance checking process could lead to ambiguity and inconsistency in the design assessments especially in a BIM-based environment where the complexity of BIM models is rapidly increasing over the years (Greenwood et al., 2010; Tan, Hammad and Fazio, 2010; Eastman et al., 2018; Dimyadi and Amor, 2013a). Visual inspection of the BIM models for compliance checking is not feasible as BIM objects could be embedded with semantically rich information (Solihin and Eastman, 2015). The highly iterative process of designing could potentially expose the design to relatively higher error rates (Preidel and Borrmann, 2018). Therefore, many existing studies had explored the potential of automating the compliance checking process to assist designers in achieving minimum compliance.

### 1.2.3 Existing automated code compliance checking system

The procedure of automating the code compliance checking process is complex and demands specific actions in defining and representing the knowledge in building regulations. It is vital to specify the type of information needed, the sources of the information, and the procedure of processing the information (Dimyadi and Amor, 2017). The rules in building regulations must first be interpreted and the building objects which are necessary for the checking process must be identified. Once the rules and building objects have been established, the relationship between both elements need to be drawn for the rule execution and reporting process (Eastman et al., 2009). Hence, the rules and building objects are the main components in an automated code compliance checking system (Eastman et al., 2009; Pauwels et al., 2017b).

Since 1969, numerous approaches had been introduced to develop automated code compliance checking systems. This was initiated by Fenves, Gaylord and Goel (1969) through the development of decision tables, followed by the conversion into programming codes for the implementation in a software application (Stahl et al., 1983). This had encouraged the development of expert systems in the CAD environment in the 1990s (Delis and Delis, 1995; Smith, 1991; Heikkila and Blewett, 1992; Myers, Snyder and Chirica, 1992). After the 1990s, the development of the automated systems shifted towards the ability of support BIM-based environment. The CORENET e-PlanCheck system in Singapore was considered as the most prominent system being developed in the early 2000s (Khemlani, 2005). It became the basis for the development of automated systems in other countries such as Solibri Model Checker (SMC) in Finland (Dimyadi et al., 2013a), DesignCheck in Australia (Ding et al., 2006), SMARTcodes and spatial program validation in United States (Eastman et al., 2009; Lee, 2010), and Statsbygg's design checking in Norway (Lê et al., 2006).

Although the workability of these automated systems had been proven through actual implementation, these applications were built through hardcoding technique, or also known as the 'Black Box' method (Kincelova et al., 2019; Preidel et al., 2018; Daima, 2020b; Ding et al., 2006; Nawari, 2018; Greenwood et al., 2010). Although the 'Black Box' method promotes significant low error rate, this method hinders the involvement and accessibility of designers to assess, modify and extend the rules in the database (Eastman et al., 2009; Ghannad et al., 2019a; Dimyadi, Pauwels and Amor, 2016a; Preidel et al., 2018). This is because the rule interpretation databases in the automated systems were not separated from the rule execution engine except for DesignCheck. In DesignCheck, the rule interpretation database was represented by Jotne Express Data Manager™ (EDM). However, the Jotne EDM could only be accessible by software programmers (Preidel et al., 2018; Shih, Sher and Giggins, 2013; Eastman et al., 2009).

As a result, the 'White Box' method became more favourable in recent studies which promotes more transparency of the internal steps for users (Preidel et al., 2018; Ghannad et al., 2019a). Eastman et al. (2009) and Greenwood et al. (2010) suggested the application of logic-based approach in extracting the complex semantics of rules. This had led to the introduction of semantic mark-up RASE methodology by Hjelseth and Nisbet (2010) as well as the adoption of predicate logic (Lee, 2010; Lee et al., 2016; Fan, Chi and Pan, 2019) and conceptual graphs (Solihin and Eastman, 2016). The semantic mark-up RASE methodology was known to be a simple and well-defined process which potentially extract the complex semantics of rules (Beach and Rezgui, 2018). The adoption of this method by other studies also proved the reliability of employing this method in various building regulations (Beach et al., 2013; Shih and Sher, 2014; Kasim, 2015; Getuli et al., 2017; Macit, İlal and Günaydın, 2017). However, the main limitation of this method as well as other logic-based approaches is that these approaches require an encoding process to be integrated into the system (Preidel et al., 2018).

Other studies focused on the direct integration of rules into the system while maintaining the separation of rule translation database from the system. This includes natural language processing (NLP) techniques (Zhang and El-Gohary, 2017a; Zhou and El-Gohary, 2017; Salama and El-Gohary, 2013b; Song et al., 2020; Xue and Zhang, 2020), visual programming language (VPL) techniques (Preidel and Borrmann, 2017a; Kim et al., 2019; Zhou, Lee and Ying, 2018; Ghannad et al., 2019a), and ontological approach through semantic web technologies (Yurchyshyna et al., 2008; Beetz, van Leeuwen and de Vries, 2009; Xu and Cai, 2020; Beach et al., 2018; Zhong et al., 2018; Zhong et al., 2012; Zhang et al., 2015c; Pauwels et al., 2011). Although these approaches have high capability to translate complex rules, the NLP techniques and ontological approach in particular were argued to be impractical for the AEC domain experts due to its complexity (Preidel and Borrmann, 2016; Zhang and El-Gohary, 2016c). In general, the VPL technique could allow accessibility for users to review and modify existing rules as well as creating new rules (Preidel et al., 2017a; Ghannad et al., 2019a). Despite its strength compared to other approaches, the application of logic-based approach is still relevant to avoid logical errors (Kim et al., 2017a). Therefore, a more practical approach in developing an automated code compliance checking system is through a semi-automated rule translation process where existing approaches are combined to extract the semantics of rules (Preidel et al., 2018).

The importance of outlining modelling requirements for BIM models in the automated system is equivalent to the importance of employing the appropriate rule interpretation technique. The most common approach for building model preparation in existing studies was the representation of Industry Foundation Classes (IFC) data model, for example the extension of IFC data schema through the creation of FORNAX objects (Khemlani, 2005), ifcXML (Yurchyshyna et al., 2008), and ifcOWL (Zhong et al., 2018). IFC is an established open interoperability standard in BIM environment (buildingSMART, 2020b). Despite this, the modelling requirements for IFC data model are complex as the conversion into this format varies according the different BIM software applications and it requires proficiency in EXPRESS language (Katsigarakis et al., 2019; Pauwels, Zhang and Lee, 2017a; Plume and Mitchell, 2007). Misclassification of IFC data could lead to data losses and errors (Wu and Zhang, 2019; Koo and Shin, 2018; Katsigarakis et al., 2019; Monteiro and Martin, 2013).

Preidel and Borrmann (2015) highlighted that the development of an automated code compliance checking system should prioritise more on the practicality of users. In recent times, the CORENET BIM e-Submission has incorporated the submission of BIM models in ArchiCAD and Revit file format as these software applications are currently used by designers to create BIM models (BCA, 2020a).

Thus, it is apparent that the modelling requirements of BIM models should be parallel to the design process to ease the burden on designers to prepare the BIM models.

## 1.3 Problem Statement

The compliance to fire safety regulations is an essential component during design phase to protect the building property and the life of building occupants from fire incidents. It is the first and most vital step in preventing the possibility of fire occurrences in buildings. Although JBPM is responsible in reviewing and approving the compliance of building designs to fire safety regulations in the building approval process, the current compliance checking process by JBPM is bounded by a set of checklists in which the designers must prepare relevant documents and calculations beforehand. Thus, designers have higher responsibility in providing an optimum fire safety level in building designs.

In a BIM-based development project, the design process is a crucial stage to create a BIM model that contain a comprehensive, accurate and reliable set of information. This information includes the passive and active measures of fire protection solutions according to fire safety regulations. Despite the importance of fire safety regulations in building designs, the regulations are seen to be subjectively complex and difficult to interpret. This could lead to ambiguity and inconsistency in the compliance checking of building designs during design stage. The relatively complex BIM models and highly iterative design process have made it more impractical to conduct a manual compliance checking process.

Accordingly, previous studies in other countries had explored the potential of automating the compliance checking process to assist designers during design process. However, the procedure of developing such system is known to be sophisticated. Since regulations were written in natural language, the regulations need to be interpreted and transformed into computer representation. The building objects or BIM properties which are necessary for the automated system must be identified. The relationship between rules and BIM properties must be established and integrated into the automated system. Commonly, the development process of the automated system consists of rule interpretation stage, building model preparation stage, rule execution stage, and rule reporting stage.

The CORENET BIM e-Submission in Singapore, Jotne EDM in the DesignCheck in Australia, and SMC software application are the dominant examples of existing automated systems in this field of study. These automated systems were built upon hardcoding technique or 'Black Box' method and were proven to be successful in conducting the compliance checking process. Although the 'Black Box' method assures low error rate in the systems, this method is disadvantageous in terms of its transparency and accessibility to the users. The development technique thereupon shifted towards 'White Box' method. This method was introduced by various studies consisting of object-based approach, logic-based approach, NLP techniques, VPL approach, and ontological approach through semantic web technologies. Despite the wide variety of approaches, challenges exist in the actual implementation of the automated system.

As the programming knowledge is quite uncommon among AEC professionals, the logic-based approach was a much-preferred approach by past studies in interpreting the rules as it promotes the ability to extract the semantics of rules without requiring any programming skills. However, it was considered as a preprocessing rule interpretation procedure and could not directly transform the rules into computer representation. Due to this, NLP techniques, VPL approach and ontological approach were explored by other studies to directly integrate the rules into their proposed automated systems. The VPL approach was seen to be a more promising solution than NLP techniques and ontological approach as the latter approaches require a certain degree of programming knowledge. While the VPL approach could provide visual representation of the rules in an automated system, the logic-based approaches remain relevant in the rule interpretation to avoid inaccuracies.

Another prevailing issue in the automation of code compliance checking process is the representation of BIM models in IFC data format. Whilst this approach was commonly applied in other studies to promote better data interoperability, the conversion from native file format of a BIM model to IFC format is a complex procedure. Inaccuracy in the conversion process could result to data losses and errors in the compliance results.

The practicality of users in employing the system should be prioritised in the development of an automated code compliance checking system. The rule interpretation technique should be able to accommodate the involvement of designers and relevant fire safety experts as they have higher knowledge on fire safety regulations than software developers. In the automated system, the rule interpretation process should also be separated from the rule execution process to provide accessibility for users to review and maintain the rules. These criteria could be achieved by employing a semi-automated rule interpretation process. In preparing the BIM models for the automated code compliance checking system, the utilisation of BIM models in native file format is more advantageous than IFC data format as it could provide better practicality for users to directly employ the automated system without having to convert the BIM models.

The limitations of existing studies motivate the necessity to develop an automated BIM-based fire regulations compliance checking system through a semi-automated rule translation process and the identification of BIM properties in native file format. This automated system could be an initial drive in providing a tool to assist designers in the compliance of BIM models to fire safety regulations in Malaysia.

## 1.4 Research Questions

Based on the discussions above, this research is undertaken to answer the following questions:

(a) What are the relevant fire safety clauses and necessary BIM properties for fire regulations compliance checking process?

(b) How to interpret the rules in fire safety clauses and prepare the BIM model for an automated fire regulations compliance checking system?

(c) How to integrate the rules with BIM properties for the development of an automated fire regulations compliance checking system?

## 1.5 Research Objectives

In consideration with the above research questions, the aim of this research is to develop an automated BIM-based fire regulations compliance checking system. To accomplish this aim, this research targets to achieve the following objectives.

(a) To establish the rules and BIM properties necessary for fire regulations compliance checking process.

(b) To structure the representation of rules and BIM properties for an automated fire regulations compliance checking system.

(c) To develop a prototype of an automated fire regulations compliance checking system.

(d) To validate the utility of the prototype of an automated fire regulations compliance checking system.

## 1.6 Scope of research

The main aspect of this research is to develop an automated BIM-based fire regulations compliance checking system. This system aims to assist designers for the compliance checking during the design process. 94 by-laws from Part VII (Fire Requirements) and 25 by-laws from Part VIII (Fire Alarms, Fire Detection, Fire Extinguishment and Fire Fighting Access) in Selangor Uniform Building

(Amendment) (No. 2) By-Laws 2012 were selected for this research. These by-laws specify the fire safety requirements for buildings. This document was selected based on the recommendation by JBPM at the time this research was conducted. JBPM stated that this document will supersede the UBBL 1984 as it provides clearer compliance rules. Selangor Government had amended UBBL 1984 through this document by substituting the content and regulations applicable to the By-laws, inserting new By-laws, and deleting certain By-Laws according to the current needs.

In the building model preparation stage, Revit software application was chosen as the platform for the identification of BIM properties. Revit has been the preferred BIM authoring software application in Malaysia since 2013 in which it had been the official platform for Public Works Department (PWD) to create a set of families in Revit (PWD, 2013; Latiffi et al., 2013). This was then followed by the utilisation of Revit as the main platform for myBIM centre which offers BIM trainings for designers in Malaysia. The myBIM centre was established under Construction Industry Development Board (CIDB) to encourage the BIM adoption in Malaysia, parallel to the Construction Industry Transformation Programme (CITP) 2015 – 2020. Thus, it could be seen that Revit is the most suitable software application to be applied in this study.

A BIM model, which is a 17-storey institutional building, was created in Revit as a point of reference. This is based on two-dimensional CAD drawings of a completed project. The institutional building was specifically chosen for this research as there are additional requirements for buildings more than 18 metre high. For instance, the requirements for firefighting access in by-law 197A of Selangor Uniform Building (Amendment) (No. 2) By-Laws 2012. The institutional building could also assist in identifying BIM properties which are related to the requirements for fire protection systems in classrooms, halls, and laboratories in Tenth Schedule as well as place of assembly in by-law 178 until by-law 188. The BIM model was created to provide guideline and illustration for the classification of objects and properties, as well as for the development of the prototype.

## 1.7 Significance of research

Numerous studies had taken various initiatives to automate the compliance checking process. However, the lack of involvement of AEC domain experts in the rule interpretation process and the inaccessibility of the systems for users to assess and maintain the rules could lead to inaccuracy during the checking process. The utilisation of IFC data model in existing studies had created more challenges in the actual implementation of the system. This research provides a semi-automated rule interpretation process through the combination of various approaches which allows the involvement of designers and accessibility for users. The utilisation of native BIM models could promote better practicality for designers to employ the system. This system could be an essential tool to assist designers in checking the compliance of BIM models to the relevant fire safety regulations in Malaysia. The artifacts of this research consisting of the architecture of the system and a prototype serve as an initial step in developing the automated system in Malaysian context. The architecture provides a guideline for developing the automated system while the prototype demonstrates the feasibility of the architecture.

## 1.8 Research methodology

In achieving the aim and objectives, this research was conducted in six stages of Design Science Research (DSR) methodology as defined by Peffers et al. (2007). Figure 1.1 illustrates adoption of DSR methodology in the research procedure. The first two stages focused on the preliminary study and literature review of the research. Review on the fire safety design process and code compliance checking process was conducted to formulate the aim and objectives of this research.

The third stage includes the design and development of the proposed work. Activities in this stage were aligned with the research objectives. Categorisation, decomposition and interpretation of clauses was first carried out, followed by the identification of BIM properties necessary for fire regulations compliance checking process. The clauses and BIM properties were then mapped together to demonstrate the relationship between both elements.

The development of the artifacts was then conducted in the fourth stage. The architecture demonstrates the comprehensive structure of the automated BIM-based fire regulations compliance checking system while the prototype demonstrates the rule execution and reporting process. In the fifth stage, the architecture and prototype were validated by expert panels. Lastly, documentation, submission, viva voce and corrections were executed in the sixth stage.

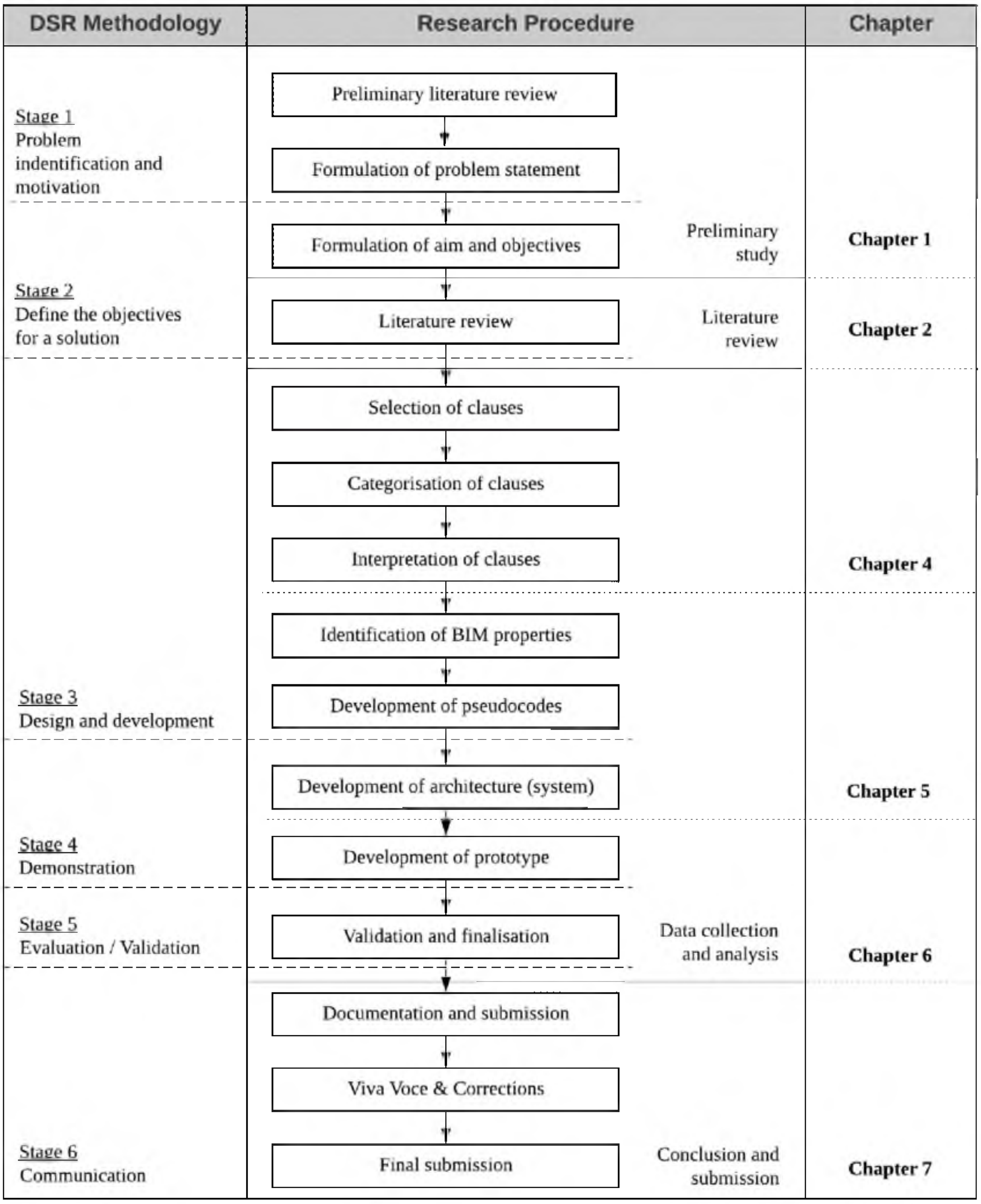


Figure 1.1 Research methodology

## 1.9 Chapter organisation

This thesis is orderly structured into seven chapters. The first chapter provides an overview of the BIM-integrated design process, the fire safety regulations in the design process, and the existing automated code compliance checking system adopted in other studies. This is followed by the formulation of research aim, questions, objectives and methodology. Scope and significance of the research are defined in this chapter.

The second chapter describes a comprehensive review on the matters related to fire safety design and compliance. The development approval process in Malaysia is introduced in this chapter followed by the progression of BIM in the AEC industry. Next, the design process is discussed which specifies the compliance checking process conducted by fire authority and the fire safety design considerations by designers. In the following section, a review on the existing automated code compliance checking system in other countries is presented. The chronological development in this field is first discussed followed by the review of existing approaches. The comparison between the approaches is presented to address the limitations which influence the way forward in this field.

The adoption of DSR methodology is elaborately discussed in the third chapter. This chapter presents a comprehensive description of the techniques applied in achieving each research objective. Next, the fourth chapter demonstrates the knowledge formalisation process of the fire safety clauses. This includes the categorisation process, decomposition through semantic mark-up RASE methodology and interpretation through interview sessions. Subsequently, the establishment of necessary BIM properties is discussed and illustrated in the fifth chapter. Chapter 5 also describes the development of pseudocodes to map the formalised clauses with the BIM properties. Next, the architecture was developed in this chapter. Chapter 6 shows the development of the prototype and the validation results. This thesis ends with Chapter 7 that outlines the conclusion of the research in terms of its findings, contributions, limitations, and henceforth, recommendations on future works.

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