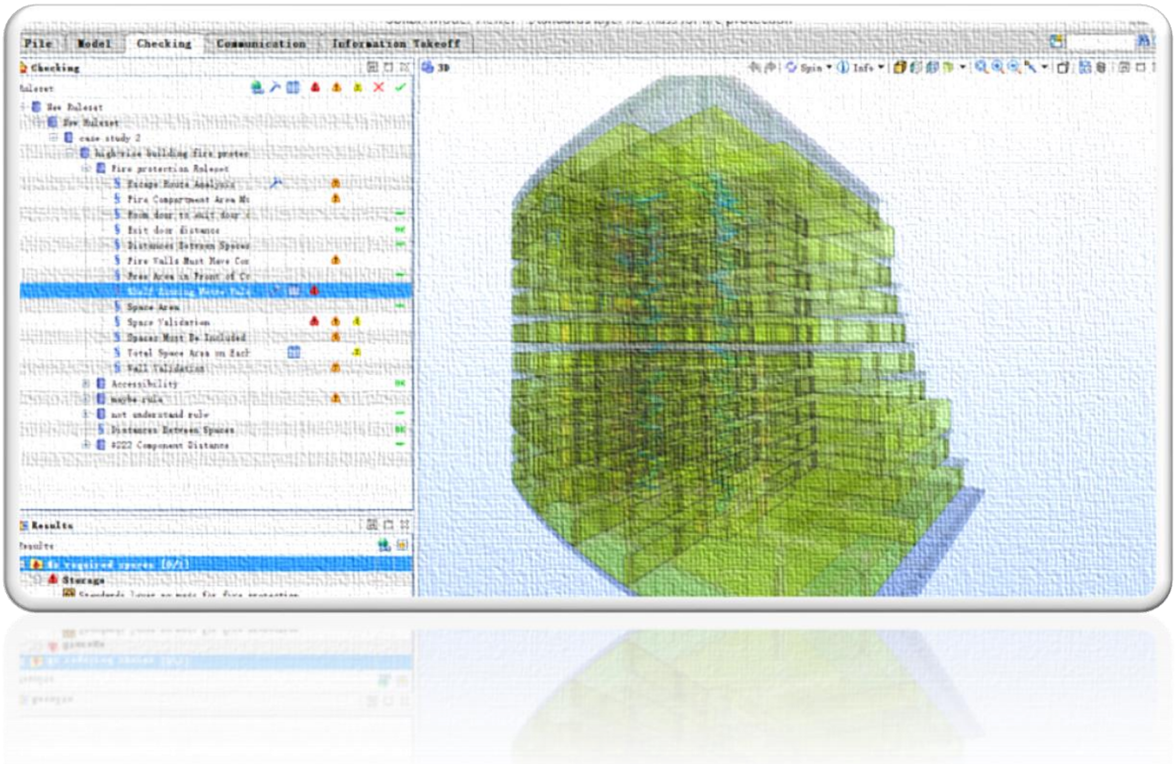
Master in European Construction Engineering 2014-15



Automated Code-checking of BIM models

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ABSTRACT

In countries such as China, building codes are checked manually during the building design and the legal-drawings checking phase. This is an important task for designers and those who work in regulatory agencies. While manual checking process always leads to ambiguity, inconsistency in assessments and delays the construction process as a whole. With the development of Building Information Modelling (BIM) technology, the automated compliance checking systems for building codes becomes achievable. It is regarded as one of the technologies with the most potential to provide significant value to the Architecture, Engineering and Construction (AEC) industry. Key challenges to a successful code-checking implementation is rule interpretation, it is critical to systematize the rules and make them tractable.

In the first part of this document, a general review of BIM implementation issues related with automated code-checking systems is presented, along with an assessment of current efforts in this area.

In the second part, a code-checking procedure is proposed, that combines the currently most widely used model checker, Solibri, with the host application and model. After researching and testing, the workflow is designed to make a link between the checking process and the model modification one.

In the last part, a case study is developed to test the proposed workflow. In this case study, LOD 100 and 300 models of a high-rise building are checked for partial compliance with the Chinese fire protection regulation for high-rise building GB 50016-2014/GB0016-2006 (Zheng, et al., 2014) (Li, et al., 2011), and Chinese design code for office building JGJ67-2006 (zeng, et al., 2006).

Until now there is only limited user experience presented in this very young rule-checking systems research. It is expected that this survey can lay out a useful workflow needed for this area to mature.

WORK STATEMENT

This is the final dissertation for Master in European Construction Engineering 2014-15. This is an individual work by Yunxue Li. Professor João Poças Martins Supervisor and Peter Ireman is moderator.

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I also thank André Monteiro from bimTEC Portugal, who helped me in Revit model development.

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CONTENTS

LIST OF ABBREVIATIONS

AEC	Architecture, Engineering and Construction
AIA	American Institute of Architects
API	Application Programming Interface
BIM	Building Information Modeling
BIMXP	BIM Execution Plan (also represented as BEP)
BCF	BIM Collaboration Format
CAD	Computer Aided Design
COBIM	Common BIM Requirements
EDM	Jotne ED Model Checker
HVAC	Heating, Ventilation and Air Conditioning
IBP	Information Building Plan
IBS	Information Building Service
IFC	Industry Foundation Class
LOD	Level of Development/Definition/Detail
LOI	Level of Information
MEP	Mechanical Electrical and Plumbing engineering
QTO	Quality Take-Off
SMC	Solibri Model Checker
SICAD	Standards Interface for Computer Aided Design
SCA	School Construction Authority

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CHAPTER 1. INTRODUCTION

1.1. Background

Building Information Modeling (BIM) is defined as a modeling technology and associated set of processes to communicate and analyze building models, which are often regarded as the next generation's approach to building design and information management in Architecture, Engineering and Construction (AEC) industry. As any other type of innovation that is adopted in the industry, BIM technology faces significant obstacles. Studies show that interoperability stands on the first stage, which should be faced in order to accelerate BIM implementation (M.P. Gallaher, 2004). Efforts on promoting interoperability among different software and modeling processes have been a priority for BIM researchers ever since this technology has appeared. The development of automatic code-checking systems using BIM works as a driver for seamless and lossless interoperability.

1.2. Methodology

A problem-solving approach (Dr S. G Naoum, 2007) is followed in this paper. Firstly, a general background of BIM implementation and the current development of automatic code-checking systems are presented. A survey about the BIM implementation situation in China (Li, et al., 2011) has been referenced. Currently, most model checkers offer text issue reports with words like "PASS" or "FAILURE" as code-checking results. Manual work is still necessary to match each issue with the host model, and then modify the model one by one. A proposal to combine both of the automated code-checking process and of model modification process is presented and after testing with different file formats, a workflow to link these two processes is developed and detailed. Finally, two case studies involving digital model prototyping (a Chinese high-rise office building respectively in LOD 100 and LOD 300) are used to test the workflow.

Specifically, this dissertation focuses on automatic code-checking for compliance with Chinese regulations, therefore, before the development of case studies, these regulations are assessed in detail, considering their use in an automated code-checking procedure. The most relevant codes considered in this document are Code for design of residential buildings GB 50096-2011 (Lin, et al., 2011), the Chinese fire protection building regulation for high-rise buildings GB 50016-2014/GB50016-2006 (Zheng, et al., 2014) (Li, et al., 2006), and Chinese design code for office building JGJ67-2006 (zeng, et al., 2006). These are the most widely used and important regulations for Chinese building construction.

1.3. Aims and Objectives

The implementation of an automatic code-checking system is a requirement of Level 2 BIM implementation as described in the Bew-Richards maturity model (NBS , 2013), and the UK government's goal by the end of 2016. In this level, we use a neutral common file format to combine the shared data from different software. Currently IFC is one of the most widely used format in automatic code-checking systems. It contributes to interoperability by transforming paper-written rules into digital ones, which could be readable in most model checkers.

1.4. Motivation & Value

With the continuing development to a Level 3 BIM implementation, a single shared project model held in a common data environment is integrated among all disciplines. Additional efforts such as the workflow that is proposed here could make a link between the designers and those bodies who are charged with enforcing building regulations (ex. Authority/verifying entity). As a result, both of these stakeholders only need to be in charge of their own field, modify the model and then update the information timely to the shared central model without time and location restrictions. This ideal situation states a valid lossless and seamless interoperability among different stakeholders (designers and authority/verifying entity) in different projects' phases (design phase and rule checking phase).

In addition, the proposed workflow is used in a Chinese high-rise office building as a case study to present theoretic research into practice. The procedures can be successfully applied to this Chinese project. We could say, it is an advanced step to apply an international model checker, Solibri, to a Chinese project based on Chinese building codes. As a result, it is hoped that this will attract more efforts on automatic code-checking systems in China, accelerate automatic code-checking implementation in Chinese building industry and stimulate Chinese BIM implementation at an earlier stage. In other words, automated code-checking procedures are viewed, not as a goal in themselves, but as a driver for BIM adoption and for the development of better BIM practices.

CHAPTER 2. STATE OF THE ART

2.1. BIM Technology Review

2.1.1. Background of BIM development

Comparing to the traditional CAD approach, Building Information Modeling (BIM) is seen as a significant improvement, which describes an activity rather than an object (ex. Software) (C. Eastman, 2008). With the influence of BIM adoption, the building industry is moving from current task automation of project and paper-centric processes towards an integrated and interoperable workflow, which maximizes computing capabilities, web-communication and data aggregation into information and knowledge capture.

In broad terms, Building Information Modeling (BIM) is a technology with the ability to design, store, analyze, manage, and share all the data in one project during the whole lifecycle. All the stakeholders, including owners, architects, engineers, constructors, managers and operators, can benefit from BIM. As opposed to traditional 2D application, instead of a modeling tool, BIM is a process which improves inter-disciplinary collaboration among all the distributed stakeholders, consistency in building data, conflict detection and enhances facilities management and sustainable analysis in the whole life-cycle of a project (Gu, et al., 2007), with following characteristics:

- Building components are no longer meaningless lines. Rather, they are symbolized by digital representations with computable graphic and data attributes. This information identifies the components to software applications, like Revit or ArchiCAD.
- Data is available during the whole process. And used for quality-takeoff, specification, energy calculation, sustainable analysis and cost estimation, etc.
- One process incorporates precise geometry with data, 3D visualization, structural details, facilities management, time control, budget control, energy-use analysis and collaboration.

Generally speaking, comparing to traditional 2D approach, the main features of a BIM process are "Coordinate and computable". BIM creates building model data, which could store and restore information to be used by the multiple project teams. Therefore, we could regard 3D visualization as an "aim", while the core of BIM is "Data". The following figure 1 depicts the difference between the traditional way of exchanging information and future's "information/data centric" model (M.A.T.Le, 2006).

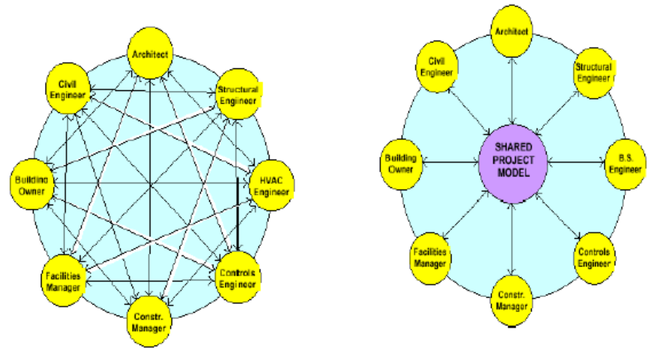


Figure 1. Today's information exchange and tomorrow's "information/data centric" model

(M.A.T.Le, 2006)

2.1.2 Current BIM development situation

In order to better understand the implementation of BIM technology in the AEC industry, a survey about the BIM implementation situation in China (Li, et al., 2011) has been referenced.

This Chinese questionnaire is from 500 participants in Beijing, Shenzhen, Chengdu, Guangzhou and Shanghai in 2011 (Li, et al., 2011). In addition, these participants are all from the AEC industry. As a result, 29% have never heard about BIM, 51% know about this technology and 20% think they would use BIM by the end of 2011. (Figure 2). Figure3 indicates that "3D visualization" for project presentation and analysis is the most useful function. "Cooperation" between stakeholders stands in the second place. Following is "integration", meaning that BIM regards the construction industry as a whole, as opposed to maintaining simultaneous partial representations of buildings tailored to individual stakeholders requirements. It "builds" a common platform during the whole life cycle to communicate the design, construction, operations and maintenance for the facilities, as well as financial information. Finally, "budget control" and "schedule optimization" are also considered very useful. When being asked about the most proper time to adopt BIM, most participants think only after BIM skills are better developed and the cost of BIM implementation becomes lower, they will consider using it.

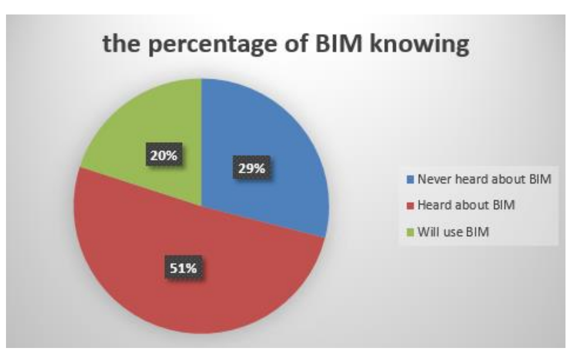


Figure 2. Awareness about BIM (Li, et al., 2011)

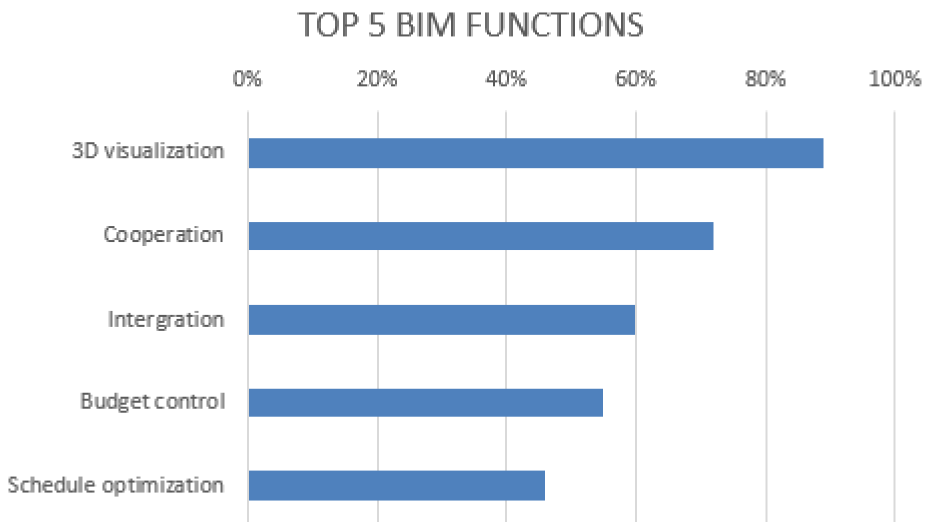


Figure 3. BIM functions ranking (Li, et al., 2011)

2.1.3 The Challenge of interoperability

As analyzed above, the core of BIM technology is "DATA". How to deal with the components' data, analysis and seamlessly transfer data between different stakeholders and among the whole life-cycle process are main issues, which requires good information management ability. When compared to other industrial activities like Aircraft and Automobile industry, information management in construction industry is not efficient. (Poças Martins J. P. i, 2010). In academic researches and professional references, we could find the words "Interoperability" regularly regarded as one of the main challenges for BIM implementation. It ranked the sixth with 41% in the survey of factors influencing the use of BIM, figure 4 (Norber W. Young Jr, et al., 2007).

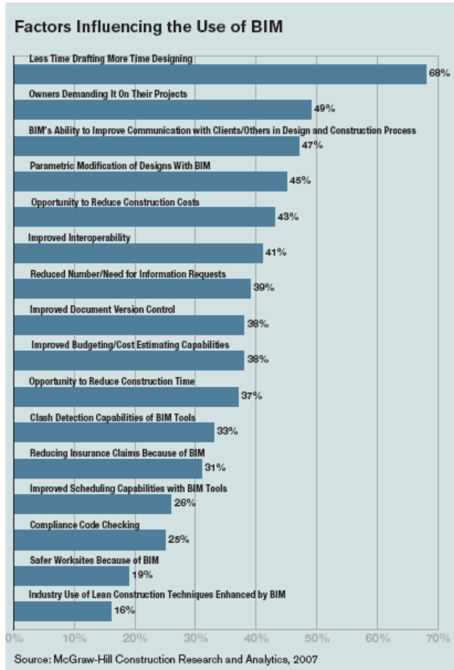


Figure 4. Factors influencing the use of BIM (Norber W. Young Jr, et al., 2007).

The definition of "Interoperability" contains two aspects, "software interoperability" and "Modeling interoperability" (João Pocas Martins, 2013). Software interoperability refers to the ability to manage and data exchange among different systems. Modeling interoperability is often defined as the ability to manage and implement collaborative relationships among different stakeholders (Norber W. Young Jr, et al., 2007), and the compliance between modeling design procedures. (João Pocas Martins, 2013).

With the more complex model representations, it has become more difficult to achieve seamless data transfer between stakeholders from one application to another. Currently, what we want to exchange is not only the simple geometry but also the geometry model information, the relations, attributions and properties for different processes (C. Eastman, 2008). Reentering data from one BIM application to another is a common feature of current construction practices, which creates wasteful and costly data duplication and omissions. Opening up new paths of automation instead of manual works become more and more necessary. Automation of exchanges helps to eliminate steps of overlapping manual copying and is essential in the pursuit of the goal of streamlined workflows.

2.1.4 Stages of BIM implementation

Building Information Modeling (BIM) chronologically follows Computer Aided Design (CAD) as a major IT related innovation in construction industry. It contains geometric visualization, the properties of its construction and maintenance, the data, which could be updated, restored and shared among different processes. Therefore, we could say, BIM innovation is not only related with technological changes but an overhaul of the whole design process. It is intended to transform how project teams work. That is why the change introduced by BIM seems to be even more violent, with more challenge and greater importance than the movement from paper work to digital drawings.

The Bew-Richards maturity model (Figure 5) (NBS , 2013) shows three levels of BIM implementation, which are not only based on the level of technology used to design a building, but also on the level of collaboration within the process.

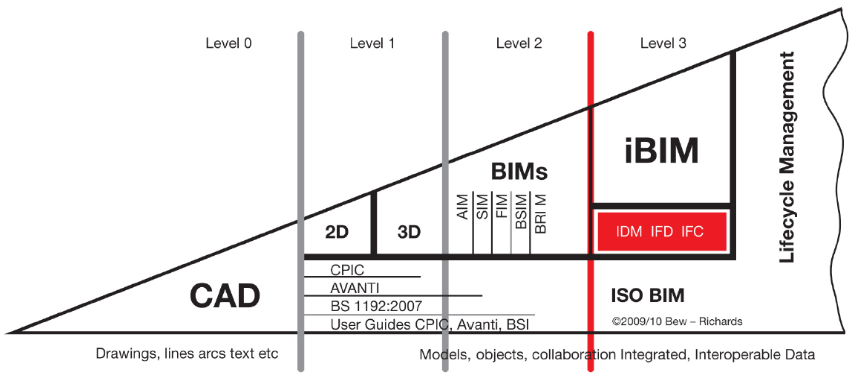


Figure 5. The Bew-Richards maturity model (NBS , 2013)

- Level 0: no collaboration

It is a paper-based process with CAD drawings, there is no formally defined collaboration between stakeholders. Output and distribution are via paper or electronic prints, or a mixture of both.

- Level 1: a mixture output

It is a mixture of 3D CAD or some modeling software, such as Sketch-Up, 3D Max, Rhino, for concept work, and 2D drawings for drafting of statutory approval documentation and production information. BS 1192:2007 is commonly used as CAD standards. In this level, there is still no BIM-based collaboration between different disciplines and each stakeholder publishes and maintains his own data separately.

- Level2: collaborative working

All parties use their own 3D CAD models, including different BIM tools for 3D visualization. Design information is shared through a common file format, which enables each organization to combine the shared data with their own ones. The most significant feature in this level is that any software involved in each stage should be able to export a common file format. Level 2 BIM implementation is the target of UK government for all public-sector work by 2016 and goal of Chinese industry by the end of 2020.

- Level 3: integrated working

Instead of using a neutral exchange format, a single shared project model is used in this level by all disciplines. All parties are able to access and modify one same central model. It is known as "Open BIM", it is a full open and integrated process with model shared among different teams on a web-enabled BIM hub (ex. BIM Cloud).

2.1.5 Motivation of automatic compliance checking system

From the Bew-Richards maturity model (Figure 2.1.5), we could find out that automatic code-checking process is implemented in Level 2 and could be continually developed with more functions in Level 3.

In the second level, some model checker applications like Solibri Model Checker (SMC) and Jotne ED Model Checker (EDM) are widely used. Currently, a common format named Industry Foundation Class (IFC) is used to build a bridge between modeling software and model checkers. It is an official standard, BS ISO 16739, developed by buildingSMART, and contains geometric as well as non-geometric data.

In the third level of BIM implementation, a shared model is used. During this period, a data model is already too large for present computers to manage adequately. Instead, a web-enabled BIM hub can be used, for example Cloud, which works as a platform for data storage, updating and exchanging. In this situation, each organization or stakeholder can download the information from a so-called "central model" from Cloud, make modifications, and then update the modified information back to the central model. This would be ideal for automatic code-checking implementation. Designers would be able to update the information in the central model by simply clicking a button. Staff in regulatory agencies could simply download the built model, work with code-checking software and then update the issues report to the host model. Without time and location restraints, a smooth workflow is built between designers and code checkers. This development helps to fully realize lossless and seamless interoperability during BIM implementation.

2.2 Automatic Code Checking Review

Following recent advancements in building construction, the need for computerizing building codes and automating the code-checking process is becoming ever more critical. Within the context of Building Information Modeling (BIM) environment, some rule-based systems are used as a model checker to check the inputted model against building codes and standards. The common feature of those rule-based systems is to generate results with words such as "pass", "fail", "warning", or "unknown". Those indicate where the needed data is incomplete, overlapping or missing. Instead of modifying model directly, this checking process normally assesses a design according to the configuration of objects, their relations or attributes.

2.2.1. Automated Code Checking Systems

Since the mid-sixties, researches about computerizing rules and preparation for code-checking were done, one of the most important studies is the application of decision tables to represent AISC standard specifications by Fenv in 1966 (L.A. & Wright, 1985). That is an if-then-novel programming and program documentation technique. Three years later, based on this concept, the SICAD (Standards Interface for Computer Aided Design) system is implemented, which is a software prototype to demonstrate the checking of designed components (L.A. & Wright, 1985).

Comparing to manual checking systems, code-checking process is potentially less error-prone. In addition, it motivates users to adopt building information models at earlier stage of the building construction process. It is important for promoting BIM technology implementation (Poças Martins J. P. i, 2010).

Nowadays, most building codes computerizing systems are based on ontology-based approaches and semantic web information. Ontology-based approaches focus on formalizing conformance requirements, which is conducted under knowledge extraction and semantic mapping. Semantic web information is about how to enhance the IFC model by using description language, which is based on a logic theory (Nawari, 2012). Most of the rules are embedded in parametric design generating systems. Therefore, the prerequisite of automated checking of design is well-developed BIM technology, which belongs to parametric design.

Most of the rules defaulted in model checking systems are global ones, such as rules associated with spatial assessment, structural integrity, safety, energy usage and so on. Customers are able to modify the parameters of each rule to match their local regulations. Once the rule structure has been defined, it is available for multiple projects. There are three widely used types of platforms for rule checking systems:

- As an application tied to a design tool, such as a plug-in. It is available to check operating model during design process;
- As a stand-alone application separated from the modeling tools, such as Solibri, which has its own rule structures and is available to multiple models;
- As a web-based application which can be available for designs from various sources

2.2.2. Current Initiatives

Until now, the application for automatic code-checking process is not yet widely used in China. Nevertheless, pioneers like the USA, UK, and Singapore have developed tools in this area that have been tested in practice.

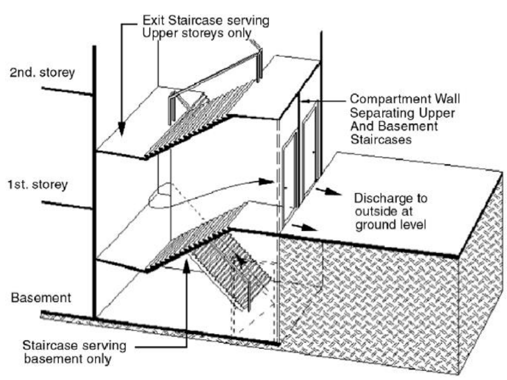
The initial efforts are from Singapore, who started to consider code checking on 2D drawings in 1995. Since 1998, they began to use the CORENET system working with IFC building models (M.A.T.Le, 2006).

SmartCODES is from the USA (Conover, 2007). Australia contributes a lot in accessibility rule checking. Recently, efforts from the GSA and US Court's are about the development of rule checking for federal courthouses (Nawari, 2012).

- Singapore CORENET system

CORENET project is the earliest code-checking system from Singapore's Ministry of National Development in 1995. It consists of three modules namely, CORENET e-Submission, CORENENT e-Info and CORENET e-PlanCheck. Related with our research area, CORENET e-PlanCheck is worth being reviewed. From 1998, instead of working on electronic drawings, CORENET began to operate on IFC building model data (M.A.T.Le, 2006). This project includes two main purposes: building code checking on building plans (IBP) and on building services (IBS).

The CORENET checking system follows four checking processes, namely rule interpretation, model preparation, rule execution and rule reporting. During the first rule interpretation process, the biggest challenge is about how to map the IFC schema for rule checking. In this project, an object-based FORNAX schema is developed, which involves IFC extension and defines the rules. During building model preparation phase, FORNAX objects are used, which contain IFC information for checking certain building regulations. Figure 6 gives an example of how FORNAX object could translate an Exit staircase shaft model into machine-readable language (C.Eastman, 2009):



ExistStaircaseShaft	
Methods	Description
IsPressurized	Check if this exit staircase shaft requires pressurization
GetFireRating	Get the fire-rating of this exit staircase shaft.
GetDischargeLevels	Fetch all discharge levels from this shaft. Calculate the nearest discharge level through this shaft for a given storey.
MinStaircaseWidth	Calculate the minimum width of the staircase in this shaft between any two storeys which this shaft serves.
SwingDirection	Calculate the swing direction relative to this shaft for a given door.

Fig 6. An example of FORNAX object-Exist Staircase shaft adopted from the Singapore Civil Defense Fire Code (C.Eastman, 2009)

By using FORNAX objects, a rule written in natural language could be directly interpreted to programming language. Until now, 92% of rules of IBP (Information Building Plan) and 77% in IBS (Information Building Service) are still using CORENET system (C.Eastman, 2009).

- Norwegian design rule checking for HITOS project

Instead of using a single platform, Norwegian design rule checking systems have been programed based on actual building projects by using multiple platforms. In addition, this system is made based on a real project named “HITOS” in Tromsø University College. This is an early Norwegian IFC-based BIM project using multiple platforms including: e-PlanCheck, SMC, Drofus, EDM, Model Server and Checker, etc. (M.A.T.Le, et al., 2006). Figure 7 shows an overview of the rule checking in HITOS project (C.Eastman, 2009), illustrating the processes:

- To validate spatial program requirements by the use of dRofus (Frode, 2005);
- To develop model by using ArchiCAD for architecture model, DDS Teknisk Partner for enginners’ model of HVAC/piping systems and Architectural Desktop for structural engineering testing;
- To merge architectural, mechanical and electrical model using EPM model server;
- To check building accessibility using SMC;
- To test other processes centered on IFC (SMC, 2009).

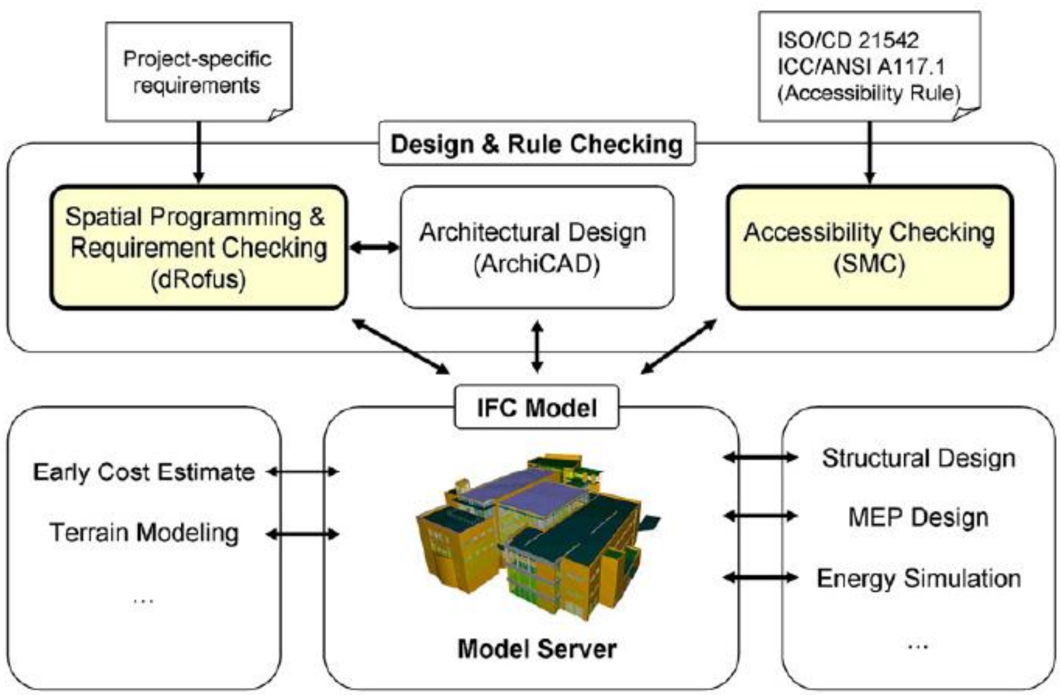


Figure 7. Process overview of the rule checking in HITOS project (C.Eastman, 2009)

2.3 Level of Development (LOD)

2.3.1 General description of LOD

LOD describes the amount of information included in a model. With the development of projects, LOD gets progressively more detailed, from generic geometry concepts to full-specified descriptions suitable for the requirements of procurement, operation and maintenance. Namely, from an approximate geometry, to precise geometry and then to fabrication level precision.

The concept of LOD appears firstly in 2008 in AIA e202-2008 Building Information Modeling Protocol Exhibition by the AIA (American Institute of Architects). It helps define the content of any part of a BIM project and it stands for Level of Development. While UK uses LOD as Level of Definition for the AIS G202-2013 Building Information Modeling Protocol (Nigel Davies, 2014). The following table 1, I made a conclusion of LOD description in both of USA and UK (Nigel Davies, 2014) (Fernanda, et al., 2010).

UK CONVENTION	US CONVENTION	DESCRIPTION (brief)
LOD1		Models communicating the performance requirements and site constraints.
LOD2	LOD100	Basic conceptual or massing models used in schematic design, which include basic areas, volumes and orientation information. All non-geometrical information is excluded.
LOD3	LOD200	Design development models including approximate quantities, size, shape, location and orientation information. Moreover, material properties and connection with analysis packages are included.
LOD4	LOD300	Production, or pre-construction, “design intent” models, representing the end of the design stages. Modelled elements are accurate and coordinated, they are suitable for cost estimation and regulatory compliance checks. Useful for QTO(Quantity Takeoff)and automated generation of drawings This level of model would typically be suitable for production construction documents and shop drawings.
LOD5	LOD400	accurate models of the construction requirements and specific building components, including specialist sub-contract geometry and data. In this level, models are with more details like rebars, furniture, finishings, mechanical equipment, insulation and waterproof layers; with better IFC compatibility and realistic rendering. This level of model would be suitable for fabrication and

		assembly but architects or engineers would rarely produce objects at this level.
LOD6	LOD500	"as built" model to show the project as it has been constructed. The model and associated date is suitable for maintenance and operations of facility
LOD7		Asset Information Models used for ongoing operations, maintenance and performance monitoring

Table 1. LOD description in the USA and UK (Nigel Davies, 2014) (Fernanda, et al., 2010).

According to table 2.3.2, model authors can define what their models can offer, while, downstream users can clearly understand the usability and the limitations of models they have received. The purpose of LOD could be summarized as:

- To help team members cooperate, to get a clear imagine of what to be included in each stage;
- To help design managers establish what information should be included in different design stages and communicate these requirements with their team members;
- To provide a standard as a reference for contracts and BIM execution plans.
  To specify BIM deliverables;

LOD specification works as a reference to enable stakeholders in the AEC industry to articulate with clarity the content and reliability of BIM at different stages in the design and construction process. Here we should note that LOD is not a project BIM Execution Plan (BIMXP), rather it is a characteristic that can referenced with a BIMXP to better define models for specific information exchanges, plan milestones in a design work plans and optimize deliverables for specific functions (Nigel Davies, 2014).

2.3.2 LOD Development

Sometimes, LOD is interpreted as Level of Detail rather than Level of Development (Reinhardt & bedrick, 22 Auguest 2013). It is essentially how much detail is included in the model element. Level of Detail defines graphical appearance in each level of model. G0 is used as a symbolic model merely to offer suggestions of where the object will exist. G1 works as placeholder to show visual component. G2 is suitable for construction, which could be downloaded as a manufacture object. G3 is a fully detailed object for manufacturing (Nigel Davies, 2014). In addition, we refer to the Level of Information (LOI) to define non-graphical attributes. Due to significant differences from one project to another, the Level of Information is harder to codify. One of the most accurate way to deal with what attributes should be included in each level is to list them in a tabular format (Nigel Davies, 2014). It is important to ensure that the information contained in each stage complies with what was defined in the contract. It is important only to include the information that is needed in each specific stage, it is better to be simple than to include all the data. Obviously, the higher the LOD is, the more detailed information it contains in the model, and modelling effort grows exponentially with LOD as is shown in figure 8 and figure 9 lists the modelling efforts required for different LODs and how much time to spend for each particular component (ex. brick wall, roof, curtain etc.) (Fernanda, et al., 2010).

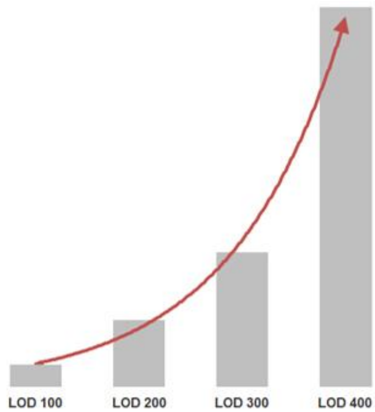


Figure 8. Effort growth and LOD (Jorge & LIMA, 2013)

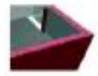
	Sections of the projects	Level of Detail (LoD)	Purpose of developing BIM	Time to model (hours)	Number of objects modeled	Screenshot from models	Time to model a single object (in hours)	Rate of increase in time	Rate of increase in time per object	Rate of increase in objects
Project 1: Commercial building	**Brick veneer**	**Precise** *(brick walls)*	Visualization	4.4	401		0.011	4.3	1.0	4.1
		Fabrication *(+ metal studs, insulation)*	Vertical alignment	18.7	1634		0.011			
	Roof	**Precise** *(only deck - as separate elements)*	Visualization	14.1	26		0.542	3.1	0.20	16.1
		Fabrication *(+ parapets, screen wall, tubes, wire meshes, HSS tubes, connections, insulation, cornice, coping, plywood)*	Vertical alignment	44.3	418		0.106			
	Curtain walls	**Precise** *(curtain walls as in typical details)*	Visualization	13.5	52		0.260	3.7	0.70	5.3
		Fabrication *(+ doors, cladding as in typical details)*	Visualization	50.5	276		0.183			
	Foundation	**Precise** *(piers, pile caps as in typical details)*	Visualization	6	94		0.064	2.7	0.67	4.0
		Fabrication *(+ grade beam, piles as in typical details)*	Design check	16	373		0.043			
	Main Structure	**Precise** *(steel columns and beams)*	Design check	29.5	927		0.032	2.1	1.56	1.3
		Fabrication *(+ inclined roof beams)*	Design check	62	1233		0.050			

Figure 9. Modelling effort required using different LODs (Fernanda, et al., 2010).

2.4 BIM Modelling Rules

Building Information Modelling (BIM) has gained much traction in recent years as digital construction technology. It is a collaborative way of working supported by digital technology, which unlocks more efficient ways of designing, creating and maintaining assets. With the rapidly rising use of building information modeling in the construction industry, the parties involved in the project have to define more precise requirements for what is to be modeled and how the models are developed.

Modelling rules are defined to enhance the quality of design and standardize the coordination contract documents by giving clarity on the requirement of BIM usages at different stages of a project. Currently, both international and national standards are available, like COBIM, which is based on the BIM Requirements published by Senate Properties (Common BIM Requirements) (Finnmap Consulting Oy; Gravicon Oy; Olof Granlund Oy; Lemminkäinen Talo Oy, 2012); National Guidelines for Digital Modelling from CRC Construction Innovation from Australia (Mitchell & Parken, June 2009); Singapore BIM Guide; AEC UK BIM Standard (Lewis Wenman; Nigel Davies; Paul Woddy; Ray Purvis; Rob Jackson, June 2015); BIM-Guide for Germany (Information und guidebook) (ZukunftBAU, 30/11/2013). In addition, various modelling rules working as local guides for a company or specific entity are also available. For example, Building Information Modeling Guidelines and Standards for Architects and Engineers from SCA (School Construction Authority) in New York City School Construction (SCA School Construction AUthority, 4/28/2014); BIM Essential Guild for BIM Execution Plan drafted by the Centre of Construction IT on behalf of BCA and the BIM Steering Committee in Singapore (Building and Construction Authority, 2013).

Taking COBIM (Finnmap Consulting Oy; Gravicon Oy; Olof Granlund Oy; Lemminkäinen Talo Oy, 2012) as an example, it includes general definitions about structure components; Structure types; labeling requirements and quality assurance. It also defines the requirements in each design phase, from schematic design, general design, tender design and detailed design phase. Moreover, it describes precisely about commissioning and facility management. Some guides like SCA BIM Standards (SCA School Construction AUthority, 4/28/2014) includes not only BIM Guidelines but also Revit Standards including file format, best practices and procedures etc.

CHAPTER 3. AUTOMATED CODE-CHECKING IMPLEMENTATION

PART A OVERVIEW

3.1 Requirement

In general, in valid automated code-checking implementation-efforts, three main parts must be covered, regulation, model and software.

Among these, regulation is a prerequisite. Research points out that rule interpretation only, takes 20-30% of the overall efforts (W.Solihin, 2015).

A suitable model is also important. Different checking goals help define which level of development (LOD) model to be used. For example, we could check the model during the concept design phase to find out whether there are any overlaps or intersections between components, or to check if the structural model is in consistent with architectural one; or if the MEP model clashes with the structural one. For such checking purposes, LOD 100 would be more suitable than LOD300 or 400. Because during this conceptual phase, design is not mature, checking with geometric information is the main task, LOD 100 could fulfil most requirements, and easy to modify. While LOD 300/ 400 model tasks too much time for making and not that suitable for such frequent modifications in conceptual design phase.

Moreover, we could also check models before the construction phase. Normally, in this period, we would like to know if the models match the building regulations or not. For example, if the numbers of exits in each floor satisfy the requirements of the Fire Protection rules. In this situation, a more developed model is suitable, ex. LOD 300.

The last part is to execute the checking process and produce the issue reports. Normally, for individual users, it is almost impossible to control the development of new standards or regulations. Moreover, most building codes are different from country to country, while most code checkers are programmed based on international standards or the application-related-countries' building codes. As a result, it is hardly able to check all local rules with international model checkers. However, it is possible to choose a suitable model checker application, edit appropriate rule-set structures and check with the model in appropriate LOD level.

3.1.1 Regulation

- **Overview of regulation interpretation**

Traditionally people define building regulations and codes in human language formats, typically in written text, tables and possibly equations with legal status. Currently, the situation in China, both designers and regulatory agencies get used to use the paper-written building regulations for code checking. There is still a long way to change from manual checking system to automatic code-checking one.

Worldwide, Regulation interpretation is not a new topic. It means lots of efforts have been done to interpret human-oriented written rules into a machine interpretable format. The most widely used is Predicate logic based interpretation. In logic, a predicate is a well-defined function to evaluate “TRUE” or “FALSE” in a sentence. During decades of development, predicate logic is well-developed general techniques for translating logical assertion into executable statements (C.Eastman, 2009).

Until now, most of efforts on language representation are only focused on the syntax and grammar of rules. However, understanding the meaning of the rules is also important, which requires experts’ knowledge and experience to interpret the semantics of the rules: the basic framework, intents, and hidden assumptions (W.Solihin, 2015). Taking as an example, CORENET ePlanCheck (Singapore Civil Defense, 2002), which uses a logic-based interpretation method, the interpretation in transforming the rules from ambiguous into more precise definition. During the process of interpretation, implicit assumptions and expectations are discovered, which could help to complete the understanding of what needs to be checked. Nevertheless, this approach may lead to underestimations to the complexity of the rules involved in the implementation (W.Solihin, 2015).

Currently, the rule interpretation process is done manually, like CORENET ePlanCheck case, it took 20%-30% of the overall effort (C.Eastman, 2009). As we know, human rule checking generates large inconsistences, because human judgments always fill in ambiguities, incorporating experience and unwritten local adaption of rules. Ontology and Semantic Web approaches are in a good orientation to solve these problems and help to move from human efforts to more automatic work, to generate consistent, precise and quantifiable conditions and constraints for each rule.

During rule translation, two aspects need to be focused on: the precondition of rule application and the properties upon which the rule applies. For example, when translating design codes on building fire protection and prevention GB50016-2006 (Li, et al., 2006). We should identify the potential fire exit and check its dimensions (length, width and height). Here we use Solibri to explain these two steps. Firstly, we should specify classifications according to space usage. Identify each exit’s components and escape route by using the classification-setting panel. Secondly, to define methods for measuring length and width. The rule-set management panel offers ability to change parametric values based on our own rules. Figure 10 shows how to set the circulation space classification in SMC.

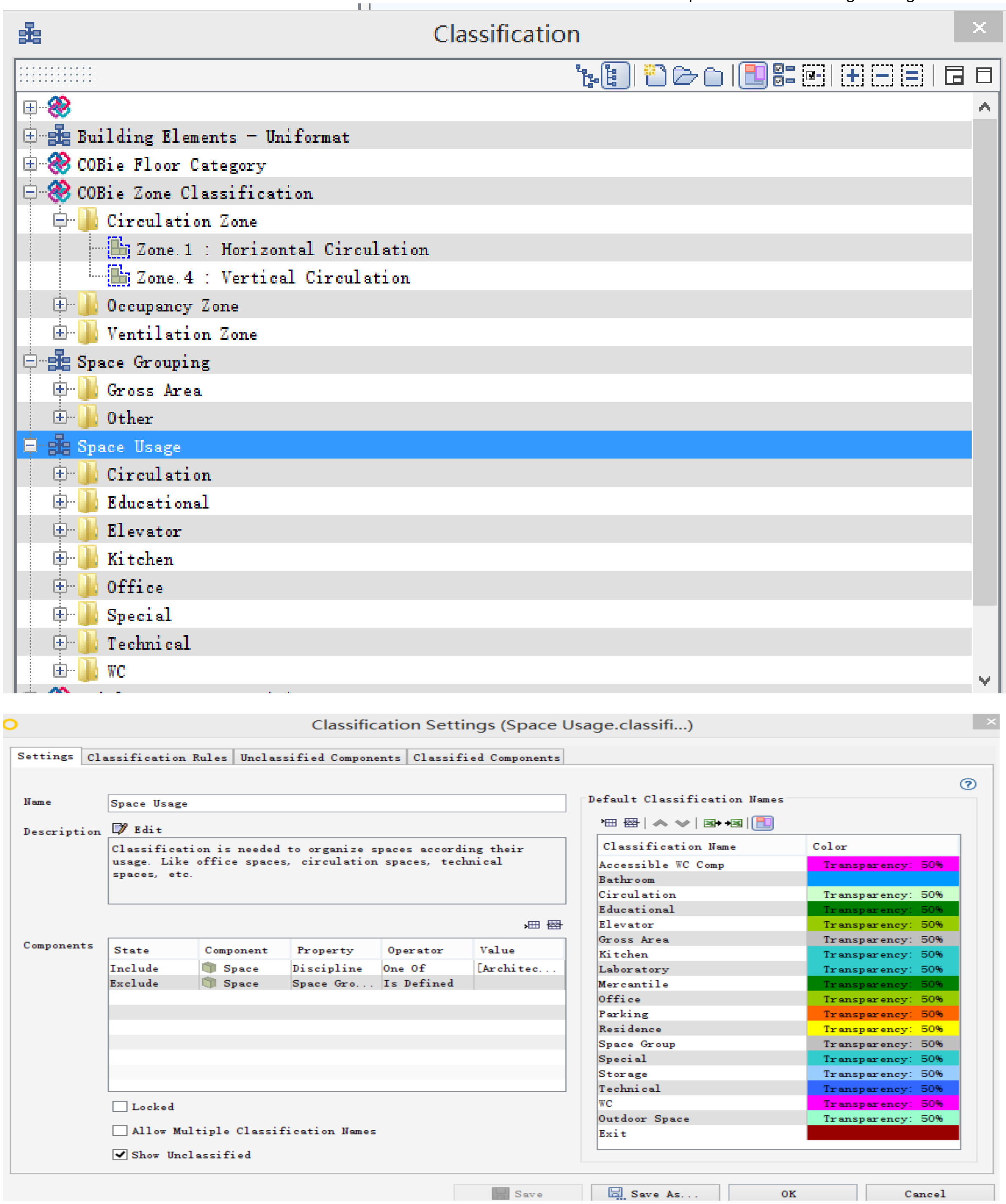


Figure 10. Setting circulation space classification in SMC

- **By-rule assessment**

During the model checking process, we could divide the regulations in four classifications shown in the following figure 11, namely, verifiable rules, non-propositions, ambiguities and others:

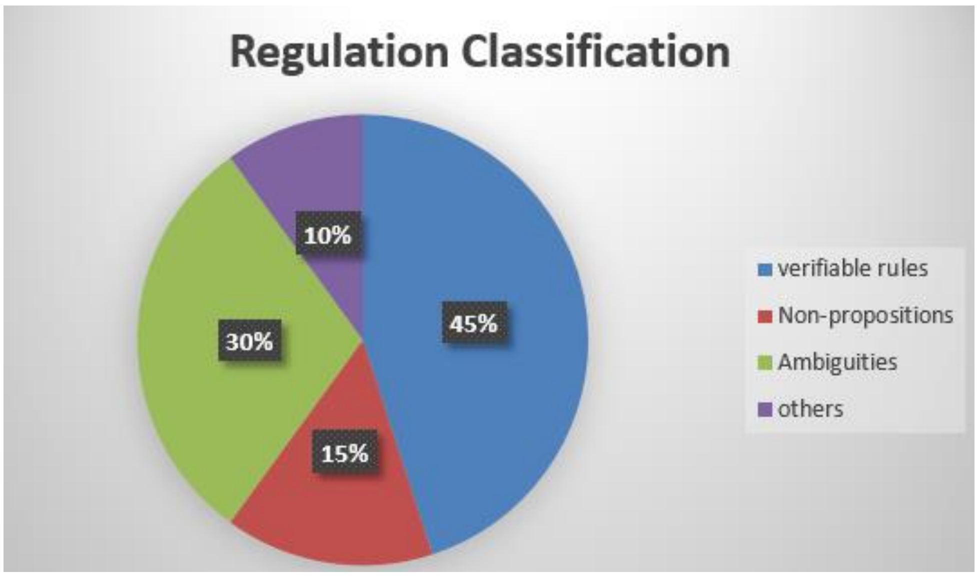


Figure 11. Classification of the rules in the regulations covered in this dissertation

For the Chinese building industry, regulations about residential buildings and fire protection, especially the fire protection rules for high-rise buildings are the most widely used. Efforts concluded in this dissertation about regulation classifications are based on Code for design of residential buildings GB 50096-2011 (Lin, et al., 2011), Chinese fire protection regulations for high-rise buildings GB 50016-2014/GB50016-2006 (Zheng, et al., 2014) (Li, et al., 2006) and Chinese design code for office building JGJ67-2006 (zeng, et al., 2006). Compared to rules related with residential buildings, fire protection codes are more complex. It is common to find that one item contains two or even more classifications, for example Item 5.3.11 GB50016-2006 (Zheng, et al., 2014).

The following four classifications are described in this section: verifiable rules, non-propositions, ambiguities and others. The complete rule classifications are presented in Appendix 1 Building Code Classification of Chinese Residential building codes and in Appendix 2 Building Code Classification of Chinese fire protection building regulation.

i. **Verifiable rules**

Verifiable rules mean that it is valid to interpret directly from the paper written rules to machine-readable ones. Among them, one typical feature is to define the rule with accurate values, for example, in residential buildings GB 50096-2011 (Lin, et al., 2011):

"Item 5.2.1. It is better not to connect each bedroom in one apartment. The bedroom area index is: bedrooms for double persons, 9m2; bedrooms for single person, 5m2. If the bedroom also acts as living room, it should be larger than 12m2."

"Item 5.2.2. Living room should be larger than 10 m2"

"Item 5.3.5. If all equipment is put one side, the clear width of the kitchen should be more than 1.5m. If on both side, the corresponding value should be larger than 0.9m."

"Item 234. The kitchen having a small area and poor ventilation must use electricity or pipe gas and set up mechanical smoke exhaust equipment. The cooking range should have fire fight measures and its depth must larger than 0.5m."

"Item 5.5.1. The residential building's story height should equal to or less than 2.80m."

"Item 5.8.7. The minimum sizes for doorways indoors should conform to the followings:"

Type	Width of the doorway (m)	Height of the doorway (m)
Building's outdoor	1.20	2.00
Apartment's outdoor	1.00	2.00
Living room' door	0.90	2.00
Bedroom's door	0.90	2.00
Kitchen's door	0.80	2.00
Bathroom' door	0.70	2.00
Balcony's door	0.70	2.00

Another typical statement is to use the words like "condition, if…then…" to interpret the meaning of "A contains B", for example "Item 212. The residential building models are classified as small, middle, large ones. Each one has a lower-limit apartment index. 18m2 is for small ones. 30m2 is for middle ones and 45m2 for large ones" in residential buildings GB 50096-2011 (Lin, et al., 2011); Item 5.3.2 from Chinese fire protection regulation for high-rise buildings GB 50016-2014/GB50016-2006 (Zheng, et al., 2014) (Li, et al., 2006):

Table 5.3.2 Conditions for providing one evacuation stair for public buildings

Fire resistance class	Maximum permitted stories	Maximum permitted building area of each floor (m2)	occupants
Class I,II	3	500	The total occupants of the second and third floor are not more than 100
Class III	3	200	The total occupants of the second and third floor are not more than 50
Class IV	2	200	The occupants of the second floor are not more than 30

"Item 5.3.8. The number of evacuation doors for rooms of the public building and the habitation building not for residential use with shared corridor shall be designed according to calculation and not be less than

two. The distance between the nearest sides of two adjacent doors in a room shall not be less than 5m. If one of the following requirements is met, one evacuation door is permitted:

- The building area of a room is not more than 120m2. The door's net width is not less than 0.9m and the room is between two exits;

- A room (not of child-care center and kindergarten, buildings for the aged) is located at the extreme end of a corridor, the straight distance from the farthest point in the room to its evacuation door is not more than 15m, and the net width of the door is not less than 1.4m;

- Places used for singing, dancing, amusement and entertainment etc. with building area not more than 50m2."

It is important to note, that a large part of rules are verifiable but they are difficult to be used in international applications. They are specific and local rules, which are only used in a particular area or country. For example, some Chinese building codes could only be carried out in China. How to apply these local rules to the international rule checking software becomes one of the most challenging issues during rule interpretation and execution phases. In this dissertation, we use Solibri Model Check in both of the case studies. It has been programmed based on Finish and Swedish building regulations and ISO specifications. Indeed, we could modify the parameters in the rule-set panel to match our local rules, but in some rules, the rule structures have been programmed with great differences, which makes it impossible to translate such rules by only modifying parameters. Here, we provide examples from the Chinese fire protection regulation for high-rise buildings GB 50016-2014/GB50016-2006 (Zheng, et al., 2014) (Li, et al., 2006):

"Item 5.3.17. The total respective width for evacuation corridor, exit, evacuation staircase and room's evacuation door of the civil buildings, such as schools, shops, office buildings, and waiting rooms for bus, ship or airplane, exhibit hall, places for singing, dancing, amusement and entertainment etc. shall be calculated according to the following requirements:

- The net width of per 100 occupants of the evacuation corridors, exits, stairs and evacuation doors of a room on each floor shall be not less than the requirements of Table 5.3.17-1. If the occupant number on each floor is not the same, the total width of the stairs on each floor may be calculated separately. For the aboveground buildings, the total width of the stairs of the lower floor shall be calculated based on the number of the occupants of the most populous upper floor. And for the underground buildings, the total width of the stairs of the upper floor shall be calculated based on the number of the occupants of the most populous lower floor.

- The total respective width for evacuation corridor, exit, evacuation staircase and room's evacuation door of the public assembly hall or room and places for singing, dancing, amusement and entertainment etc. which are in the basement or semi-basement shall be calculated based on 1m per 100 occupants;

- The total width of the external doors on the first floor shall be calculated depending on the occupants on the floor or the most populous floor above. If the external doors are not used for evacuation purpose for the upper floors, the width may be determined by the occupants of the floor;

- The number of evacuation occupants of video room and cinema shall be calculated based on 1 occupant per square meter according to its building area. And the number of evacuation occupants of other places for singing, dancing, amusement and entertainment etc. shall be calculated based on 0.5 occupant per square meter according to its building area;

- The number of evacuation occupants in shops center be calculated by the building area of business area of each floor multiplying area convert value for aboveground shops should be 50%-70%, and for

underground shops, it shall not be less than 70%. The conversion factor of the number of evacuation occupants can be determined according to the requirements in Table 5.3.17-2."

Table 5.3.17-1 The net width per 100 occupants of evacuation corridors, exits, stairs and a room's evacuation doors (m)

Stories				
		Class I & II	Class III	Class IV
Aboveground	1st &2nd floor	0.65	0.75	1.00
	3rd floor	0.75	1.00	-
	4th & upper floors	1.00	1.25	-
Underground	The distance between the lowest floor and the entrance ground is not more than 10m	0.75	-	-
	The distance between the lowest floor and the entrance ground is more than 10m	1.00	-	-

Table 5.3.17-2 The conversion factor of number of evacuation occupants in shop business area (Person/m2)

Floor	-2F	-1F,1F,2F	3F	4F & upper floors
Conversion factor	0.80	0.85	0.77	0.60

It is a local rule for Chinese designers to calculate the total respective widths for evacuation corridor, exit, evacuation staircase and room's evacuation door of the civil buildings.

Considering, for example, the calculation of this total width in two different scenarios, each with the same area of 2000m^2: a public assembly hall and a shop center on the ground floor. Firstly, we should notice that: the definition of "first floor" in China means where the floor has the similar height to the outside level. It would be called "Ground floor", in UK and most European countries.

According to the above rule definition and table, we could figure out the minimum width of a public hall (D_{hall}) and a shop center (D_{shop}):

$$(\text{Dhall}) = \frac{2000 * 1}{100} * 0.65 = 13m$$

S=2000m2

1m per 100 occupants

The net width per 100 on the ground floor is 0.65 (m)

Equation 1. Minimum width for public hall

$$(\text{Dshop}) = \frac{2000 * 0.5}{100} * 0.65 * 0.85 = 5.525m$$

S=2000m2

0.5m per 100 occupants

The net width per 100 on the ground floor is 0.65

The conversion factor of number of evacuation occupants on the ground floor is 0.85(Person/m2)

Equation 1. Minimum width for shopping center

These above formulas are local and typically used in China to obtain the total width of exits, which is impossible to interpret into machine language to be used in a Finish-standards based software, without programming and resetting the rule structure.

Another example shows some typical and local components used in Fire protection Code (Zheng, et al., 2014) (Li, et al., 2006):

"Item 5.3.5. The evacuation stairs in the following public buildings shall be enclosed staircases (including enlarged enclosed staircases on the first floor) or outdoor evacuation stairs.

- The buildings for inpatients in a hospital or sanitarium;

- Hotel;

- Public assembly buildings with more than two stories such as shop etc;

- Buildings with parts for singing, dancing, amusement and entertainment etc. and more than two stories;

- Other public buildings with more than five stories."

"Item 5.5.12. Public buildings of Class I & II with more than 32m must use smoke proof staircase; with not more than 32m should use enclosed staircase."

The definition of these three categories of stairs shows clearly in figure 12, respectively open staircase, enclosed staircase and smoke proof staircase (qi, 2002). Such local components are not defined in SMC, in the rule-set management panel, there is no way to customize staircase type.

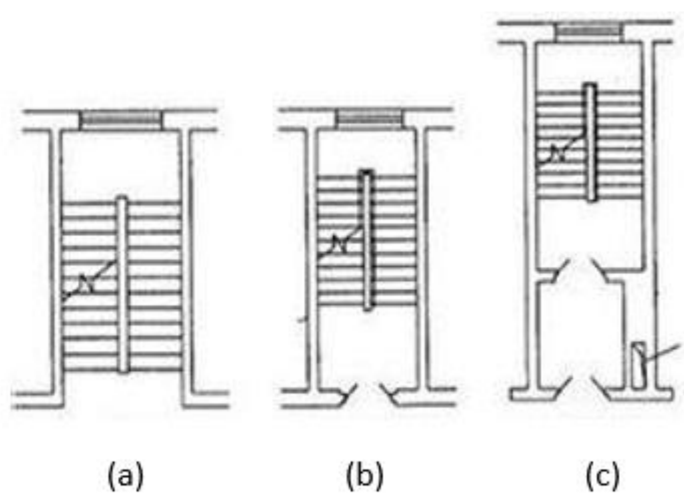


Figure 12. (a) Open staircase (b) Closed staircase (c) Smoke proof staircase (qi, 2002)

Otherwise, there are some rules about escape route calculation, fire shutter doors, automatic sprinkler systems are also not difficult to defined by rule-set management in SMC. In conclusion, it is clear to see that it is impossible to check all Chinese building codes in an international building code checking software.

ii. Non-propositions

Non-propositions indicate that the rules can not be translated into TRUE or FALSE. Instead of proposing, these rules are usually used for definitions, such as the definition of firewall, fire rate, smoke evacuation, high-rise building etc. For example (Lin, et al., 2011) (Zheng, et al., 2014).

"Item 251. Residential building designers should compute the average apartment area and used area factor. They should be computed as followings:

The average apartment area = total building area (m2)/ number of apartments

Used area factor = total used area (m2) / total building area (m2)"

"Item 252. The used area should be computed in the following way:

The used area indoors includes bedroom, living room, transition, corridor, kitchen, bathroom, toilet, store space and closet.

For the apartment that has more than one story, all the areas of its indoor stairs should be added into the used area.

The chimney, ventilating duct and pipe that are not included in the construction area should be included in the used area.

The thickness of wall's decoration should be included in the used area."

"Item 1.0.2. This code shall be applicable to the construction, extension and renovation of the building specified as follows:

- Residential buildings of 9 stories or below (including residential buildings with commercial service facilities)

- Public buildings not over 24m high

- Single story public buildings over 24m

- Underground and semi-underground buildings

- Factory and storage building"

iii. Ambiguities

Ambiguous rules are not objective. They normally include words such as: close to, far from, maybe, etc. Examples in both of residential and fire protection rules (Lin, et al., 2011) (Zheng, et al., 2014) (Li, et al., 2006) are showed in the following:

"Item 5.2.4. Corridors and Dining room could have indirect lighting. Its area may not be smaller than 10m2."

"Item 281. The size of turning corridor should be suitable for moving furniture."

"Item 222. Bedrooms should have daylighting and natural ventilation. When the bedroom is lighted through corridor, it should have good ventilation, safety and privacy."

"Item 232. Kitchens should have cooking range, washing pool, chopping board place and fixed built-in closet. If not, there should have enough space for these things."

"Item 223. Living rooms should have daylighting and natural ventilation. Its area may not be smaller than 10m2."

"Item 3.2.4 When the public entrance and exit of the building are under the balcony or the side corridor, some safety measures should be adopted."

"Item 5.2.4. It is better to design kitchen near to the access of the house."

"Item 5.6.1. It is better to have balcony or terrace."

"Item 5.3.18. Public assembly building's window and balcony etc. should not be installed with metal barriers. If a metal barrier has to be installed, there shall be a device that can open the barrier from the inside easily. Assistant evacuation facilities should be installed on window and balcony etc."

"Item 6.9.7. For the basement and semi-basement, some measures, such as water prevention, damp prevention, and ventilation, might be adopted. For the light shaft, the facilities, which can prevent the rainwater entering and can drain the water, should be installed."

iv. Others

"Others" in this graphic mostly indicate that the rule-checking process must depend on the complexity of the models. This means some rules are only suitable for a particular level of model development, which might not be compatible with the design stage when the model is being developed.

Many rules in Chinese code require higher LOD models, or require more accurate components. As a result, this hinders the automatic code checking process. For example, in *"Item 236 For the kitchen using firewood or processed coal as fuels, smoke windows and chimney should be set up to avoid smoke to return and mix up."* Smoke windows and chimney are needed for this code; in*" Item 5.2.3 In the living room, the wall against which we arrange or put our furniture, should longer than 3m."* the furniture family (ex. Sofa) is necessary; And in *" Item 5.4.1 For a bathroom, a toilet; a Washbasin and a bath device are three necessary sanitary equipment. Meanwhile the area of the bathroom should more than 2.5 m2",* the sanitary equipment must be contained in the model for checking this rule.

As the efforts grow exponentially with LOD (Jorge & LIMA, 2013), it would be too complex and impossible to use a well-defined high LOD model to do all code-checking processes. For example, it is unfeasible to require LOD 500 models in the concept stage or to develop costly LOD 400/500 models for concept design checking purposes. Currently, it proves LOD 300 is sufficient and suitable to be used in most code-checking systems (W.Solihin, 2015). It contains specific systems, information about quantity, size location and orientation.

We hope with the development of modelling, it would be possible to use lower LOD model for code-checking. In this situation, we prefer to use families from building component and system manufacturers instead of self-making ones, and these families could be offered by different companies with various functions, for example families like reinforced column, a fire bolt, a fire shutter and so on. These families are already modelled. Currently, we could directly download these families represented components from the homepage of the company and even buy construction components from suppliers. We hope that in the future, some agencies could be in charge of checking the geometry and non-geometry information, making standards, in order to guarantee the quality of such supplied families. If such a process develops, designers would be able to make a lower LOD model with good qualified families in short time and easily to be used in automatic code-checking process.

3.1.2 Model

It is crucial that the involved model supports the checking system. That is to say the entity types that will be checked are included in the data structure and have properties that match the building rules. For example, *"Item 231. The kitchen's area should fit for the followings: If the fuel is pipe gas or liquefied petroleum gas, kitchen's area should be larger than 3.5 m2."* (Technology, Dec.2000). Here should be noted that the model must include a "type of fuel" property for kitchen appliances. This means two things: the model follows modelling rules (such as LOD requirements) and the data structure (ex. IFC) includes all relevant entities and properties.

Traditionally, the objective is displayed by 2D drawings. These drawings must look visually correct and contain varied information needed for later rule checking process. Today, with the development of object-based building models, objects being checked have a type and more complex properties, the requirements for code checking become stricter. For example, a stair object must be converted with properties like risers, tread and run orientation. Only if these basic properties are defined, can a stair be identified as such in model checking applications. Concerning semantic issues in BIM models, modelling rules must be adopted to keep the model valid and reliable.

- **Semantic issues and semantic web technology**

With BIM we have moved from the 2D world of lines and shapes into the 3D world of objects and data. For example, a window component is not just a rectangle, it is a 3D object with properties such as geometric information, suppliers' information, cost and links with documentations. As people have become more familiar with BIM tools, it is no longer practical for the user to focus only on the visual inspection. We also make great use of the properties from building geometry, dealing with abstract and semantically rich information, which are not always presented in drawings (W.Solihin, 2015). In this phase, it becomes more and more difficult to keep lossless and seamless interoperability for exchanging data (Poças Martins J. P. i, 2010).

Ideally, the information could be easily shared, retrieved and then used for various engineering or environmental simulations and analyses, for example to calculate energy consumption, make construction 4D simulations, optimize time schedules and automatically check code checking. However, the fact is, individual building information modelling applications store information in their native formats, which imposes difficulties for obtaining and reusing the data in subsequent applications downstream in the workflow ant the insufficient sematic definition of exchange information prevents achieving the full potential of BIM through seamless interoperability. (Belsky & Brilakis, 2015).

In order to address this issue, semantic web technologies are developing very fast in recent years. Data kept in the web should use standard data descriptions, so it is easy for downstream machines to understand. Additionally, the semantic web technology gives a formal definition of web resources by means of ontologies. Therefore, it is possible to automatically reason over large scale web repositories, infer new information from existing data source and make use of them (Belsky & Brilakis, 2015). Generally to say, all asset data is stored in a web, which can be queried, analyzed and linked with other databases (Farias & Nicolle, 2010). It helps us to solve semantic issues and improve interoperability across different BIM domains.

- **Adoption of BIM modelling rules**

Modelling rules like COBIM (Common BIM Requirements), Singapore BIM Guide, National Guidelines for Digital modelling, the VA BIM guide and AEC UK BIM standards are used to address the growing data requirements, to arise the applications of standards, to help build a unified, practical and pragmatic design environment and to enhance the practical implementation of BIM for the AEC industry (Figure 13). These modelling rules range from implementation plan, collaborative BIM working, interoperability, model structure (model creation, usage, LOD and object properties), model management to model methodology to documentations and presentation styles.

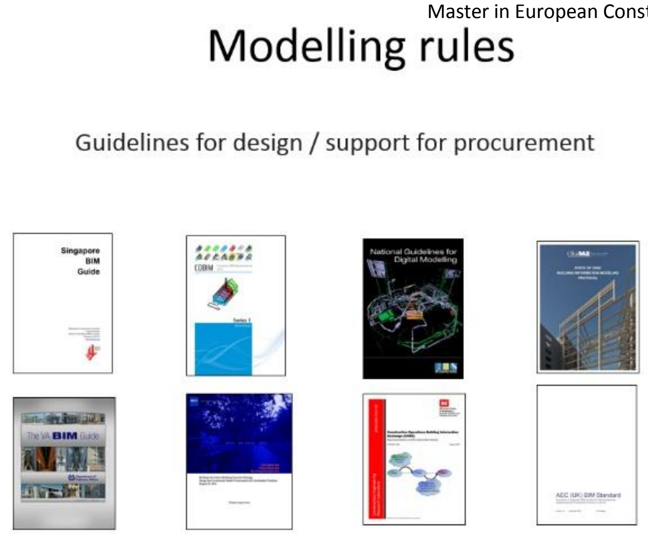


Figure 13. Modelling rules (Dr John Keung, 2013)

In order to make the extensive design and construction information available to asset operators and managers, it is important to notice that these guides and modelling rules are truly useful if as many companies adopt is as possible. Comparing to the UK, USA, Singapore, Chinese BIM implementation stands in an immature stage. Currently the national standard is not available, but provinces like Beijing, Shanghai and Guangzhou promulgated their local BIM modelling rules one after another in 2013, 2014 and 2015 (Ye Dahua, Qu Jishui, Guming, Yejia, 2014). Main contents are similar, including general introduction and background of building information modelling, the resources (modelling software, BIM-based collaboration platform, BIM component and component library), Level of Development and delivery requirements. These three cities play as leaders of Chinese BIM implementation, while Chinese national BIM modelling rule is still in preparation phase. In 2010, China’s Department of Housing pointed out: “By 2020, 90% of the following new to be built projects must be delivered using building information modelling during the design phases, construction phases and maintaining phases. These projects include all centrally procured government construction projects, the public buildings declaring to be green buildings and ecological residential buildings. (Li gao, 2015)” This strategy is similar to the one followed in the UK, to reach BIM level 2 by the end of 2016. This strategy would potentially accelerate BIM implementation in China rapidly and also the national building standards enactment and usage.

In this dissertation, the BIM model was developed based on the requirements from the Shanghai BIM Guide, which is the latest building modelling guide in China (Cui, et al., 2015). It gives general requirements of modelling and special requirements in each of building phases from conceptual design, detail design, delivery documents, construction phase and maintenance period. In appendix A (Cui, et al., 2015), the suggestions of LOD in each phase are listed.

- **Visual model checking**

As expected, some rules can be checked visually. This means that without the help of model checking application or software, it can be easier to check the rule visually instead. For example, *"item 5.3.3. Building for the aged, children's activity room like children's studying room and playroom in the nursery and kindergarten should be set up independent buildings. If it has to be set up in other civil buildings, it should be designed with an independent exit and shall meet the requirements of Table 5.1.7 in this code"* (Zheng, et al., 2014) (Li, et al., 2006) . It is not easy to translate "independent buildings" into machine-readable language, but it is easy to see if the building is independent or not. A similar example in GB 50096-2001 (Lin, et al., 2011):

> *"Item 5.3.5. The evacuation stairs in the following public buildings shall be enclosed staircases or outdoor evacuation stairs.*
>
> *- The buildings for inpatients in a hospital or sanitarium;*
>
> *- Hotel;*
>
> *- Public assembly buildings with more than two stories such as shop etc;*
>
> *- Buildings with parts for singing, dancing, amusement and entertainment etc. and more than two stories;*
>
> *- Other public buildings with more than five stories."*

In order to use automatic code-checking process, firstly we should classify the building styles: hospital, hotel, public shopping place, entertainment building and others. Then we need group them in each classification with different height, here we should define two groups with "*story more than five floor*" and "*story not more than five floor*". Then we should also interpret what "*enclosed staircases*" and "*outdoor evacuation stairs*" mean. It would be not easy to translate local stair styles into worldwide used software. Instead of using automatic code checking systems, it is easier for Chinese design-checkers or designers to recognize the stair styles and if the stairs achieve the requirements or not at first sight. It can be said that although visual checking is a less formal approach, it is sometime much easier than automatic checking and it is often a suitable approach.

3.1.3 Software

In automatic rule checking process, software is used to execute rule-checking process and produce issue reports. The execution phase combines the prepared model with the rules that apply to it. For most software, before real checking process occurs, a pre-checking phase is important to pre-check the imported IFC model, to verify if it carries the validate properties, names and objects. Then according to the user's requirements, some pre-set rules will be used for specific checking purpose. As a result, a report with the words such as "pass", "fail" or "warning" or "unknown" is generated automatically to point out the issues found in the imported model.

Normally, a simple and intuitive mean to identify the issue is by reference to the location in the model coordinates, and with a model image in order to find out the problem easily.

In recent years, a number of software platforms have been developed for automated rule-based code checking. Three of the most common used are Solibri Model Checker (SMC); Jotne ED Model Checker (EDM) and Fornax. In the workflows and case studies presented in this document, Solibri Model Checker is used as the model checker for automatic rule compliance process. It is a JAVA-based along platform application in which IFC model is readable. It maps IFC model to an internal structure facilitating access and processing (SMC, 2009) with features of advanced clash detection and management; deficiency detection and verification of elements from architectural, structural and MEP models.

Variety Build-in from SMC is useful, like a library for pre-checking a model, shape overlaps, name and attribute conventions, object existence, fire code exit, path distance checking etc. Otherwise the rules can be parametrically varied by table-set control parameters. And the new rules can be edited in JAVA using the SMC application programming interface (API) (Nawari, 2012).

Jotne EDModelChecker (EDM) is another software providing an object database and supporting the open development of rule checking. It use EXPRESS language, which is the same language as the IFC model schema. FORNAX is the first substantial effort in building code from Singapore. It is used in CORENET system and later developed by nova CITYNETS Pte. Ltd on top of EDM Model Checker. Different from the previous mentioned two software, FORNAX has a C++ object library to derive new data and generate extended views of IFC data (EDM, 2009), see Figure 2.2.1.

PART B

3.2 Workflow

The code checking process can normally be divided in two phases. The first one occurs in the conceptual phase, driven by the designers and the second is in the legal drawing checking phase before construction stage, conducted by the authority or verifying entity. In both of these phases, the IFC format can be used as a bridge to export from Revit and then import into Solibri Model Checker for rule checking. Revit was adopted as the modeling tool in this work because it is widely used in both Portugal, where the dissertation was developed, and China, where the case studies are based. Other software tools could be used for this purpose as long as they are IFC and BCF compatible.

In addition to the previous known workflow from model maker software (ex. Revit) to code checking software (ex. SMC), it is quite important to develop an additional procedure to add extended reporting capabilities in order to continually use these issue reports to support the model modification process. This is the aim of this dissertation: to help complete the workflow from "model development, to code checking to model update".

In order to build a bridge between BIM authoring software and model checker application, BIM Collaboration Format (BCF) is used in both of these workflows. Solibri and Tekla Corporation introduced the BCF concept in 2009 (SMC, 2009) to provide an efficient collaboration for model Quality Assurance and Quality Control. In SMC, issue reports can be saved in BCFzip format versions 1.0 and 2.0 and then import into Revit for modification. Later, Autodesk developed an Add-in for Revit named BCF Plugin, which allows the import/export, creation and modification of BFC files within Revit. This BCF Plugin can work as an add-in within the Revit environment, or work as an independent application to create and import/export BCF file. In this context, the difference between an Add-in and an independent application is that only the first one is able to directly link with the host model by clicking the function button named "VIEW".

The following two workflows show how this process works in two situations, namely, in the conceptual design phase and in the legal code-checking phase. The detailed processes are presented in the next chapter as two case studies.

3.2.1 Workflow 1

Conceptual phase of automatic code-checking process

In the conceptual phase, the designer in the first lane of the diagram is normally an architectural or a structural designer who develops the models. The designer in the second lane will act as a design reviewer. He can be the same person as the actual designer. By using model checker, he can find the incorrect issues and modify the model during the conceptual phase. It could help him to develop a model with better quality. Or he could be someone else in the design team who is in charge of model quality checking.

Firstly, the designer develops a BIM model in Revit and export IFC file to be used in SMC. Secondly, the designer in the second lane begins to implement code-checking process and generates an issues report in a BCF file. After that, the first designer imports the BCF file into Revit, modifies the issues and completes the host model. Meanwhile he could make comments to tell other collaborators about the correction situations, with words like “This issue has been solved in Revit” or “This issue need to be checked again in SMC”. Then, the modified IFC model could be imported in SMC again and checked until all issues have been solved. Shows in figure 14:

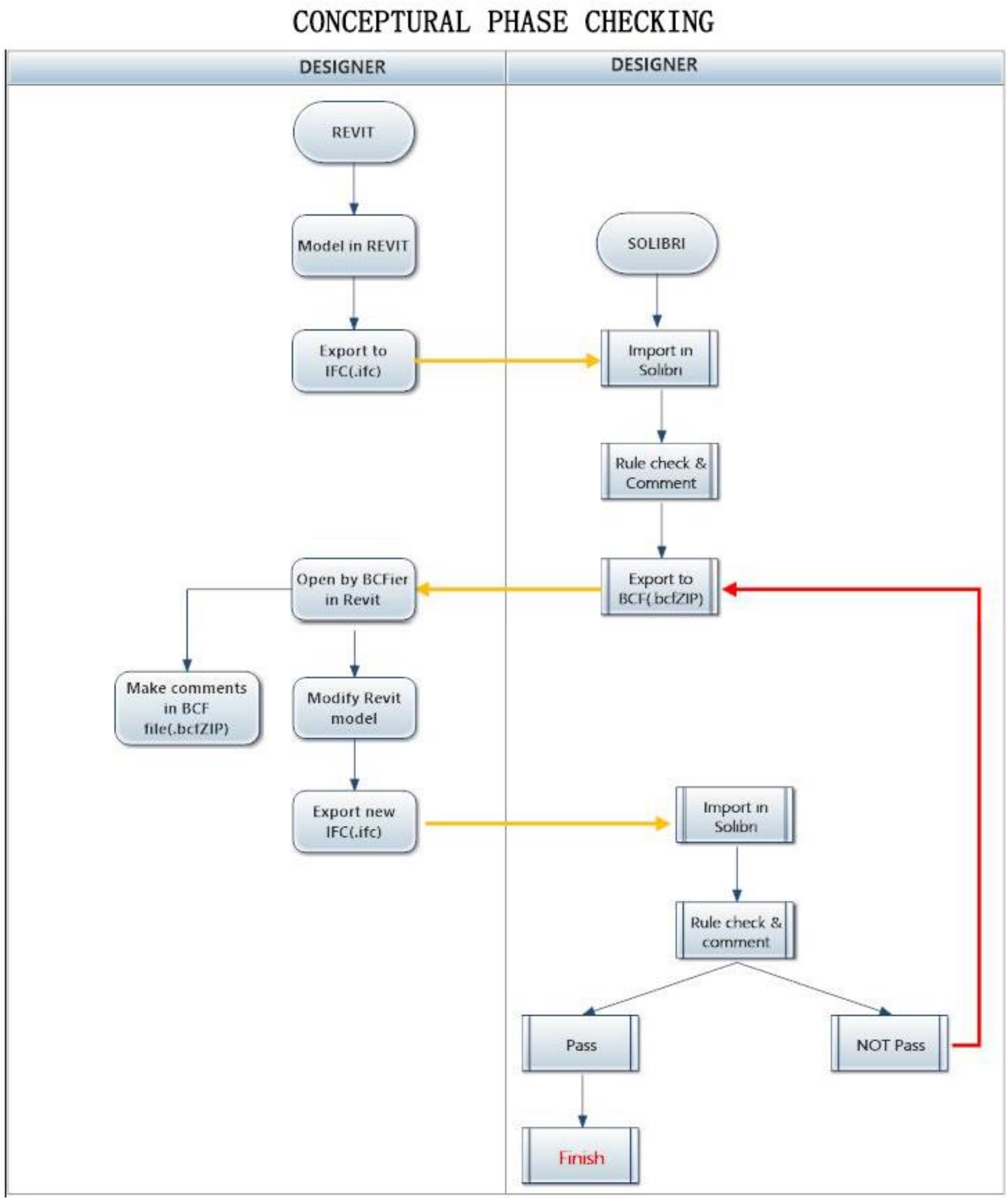


Figure 14. Conceptual Phase of automatic code-checking process

3.2.2 Workflow 2

Legal Phase of automatic code-checking process

This workflow describes an automatic code-checking process between two entities, the building design department and regulatory agency. This is a compulsory phase to check the building codes before carrying out any work on site.

Firstly, the designers develop the BIM model in Revit, export it in IFC format and send it to the regulatory agency for code-checking. Authorities in the regulatory agency check for compliance with building codes in SMC and export issue reports in BCF files and then send them back to the design department. The designers can verify the issues visually and link the issues directly to the host model with Revit's "VIEW" function. After modifying the models, designers could on one hand save the file in IFC format and on the other hand, make comments to inform their team members about what has been done about each issue. After that, authorities in the regulatory agency can check this newly-exported IFC model in SMC again, until all problems have been solved. Shows in figure 15:

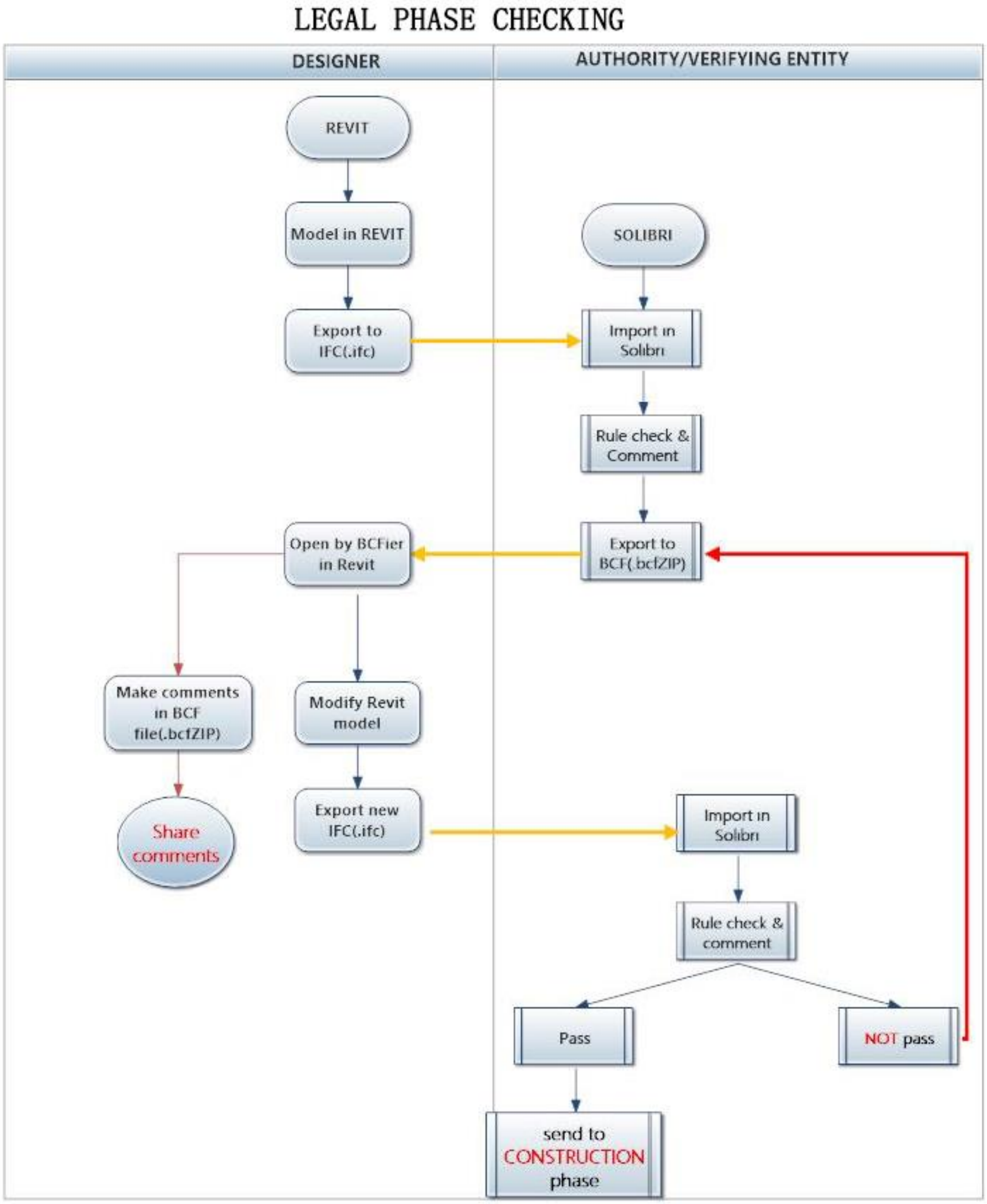


Figure 15. Legal Phase of automatic code-checking process

CHAPTER 4. CASE STUDY

4.1 Conceptual Design Phase

In this part, an LOD 100 prototype is used to check the Chinese building code. This is a high-rise office building in conceptual phase. The Chinese building code for office buildings JGJ67-2006 (zeng, et al., 2006) and Chinese fire protection regulation for high-rise buildings GB 50016-2014/GB50016-2006 (Zheng, et al., 2014) (Li, et al., 2006) are used to make the rule-set.

Following the process outlined in Workflow 1, presented in the previous chapter, the case study about the conceptual phase model-checking follows these steps:

(1). Developing the model in Revit

The model is developed in Revit and then exported to IFC (.ifc) format.

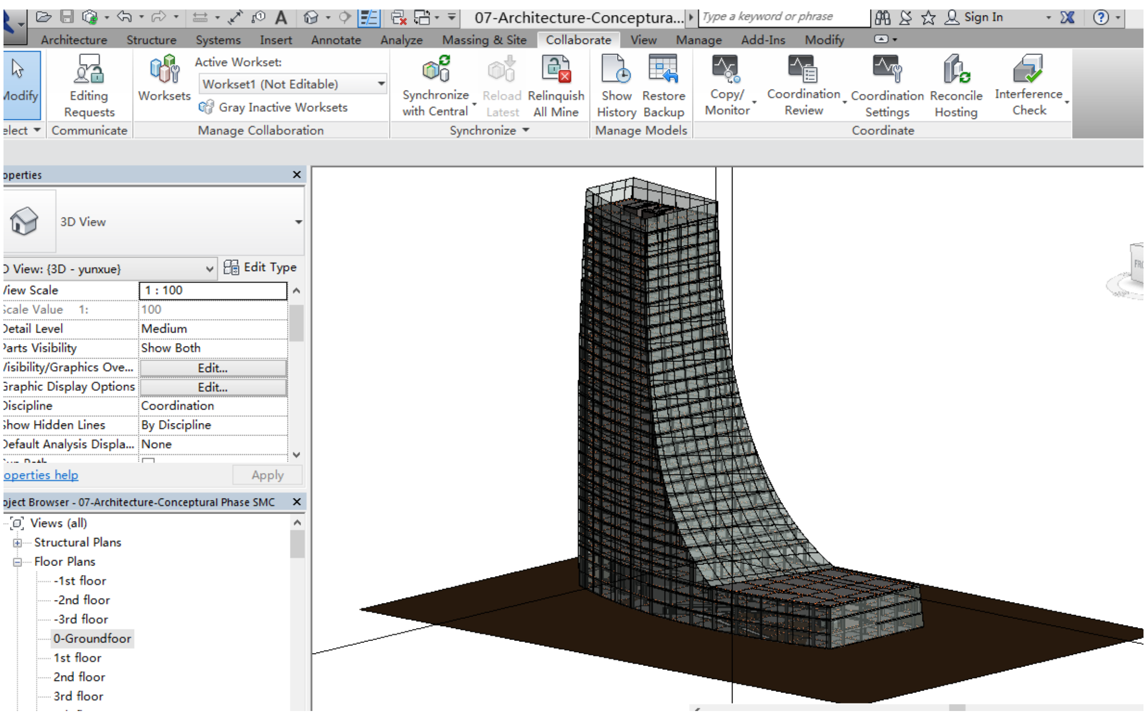


Figure 16. Model in Revit

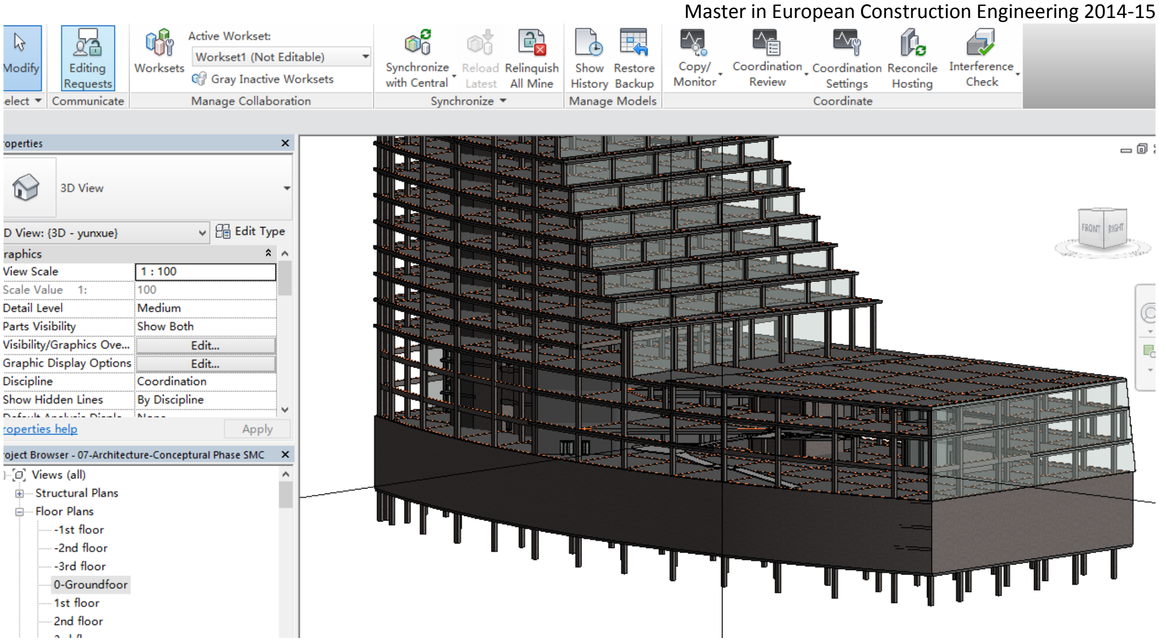


Figure 17. Model in Revit

(2). Solibri Model Checker

- Import IFC to SMC

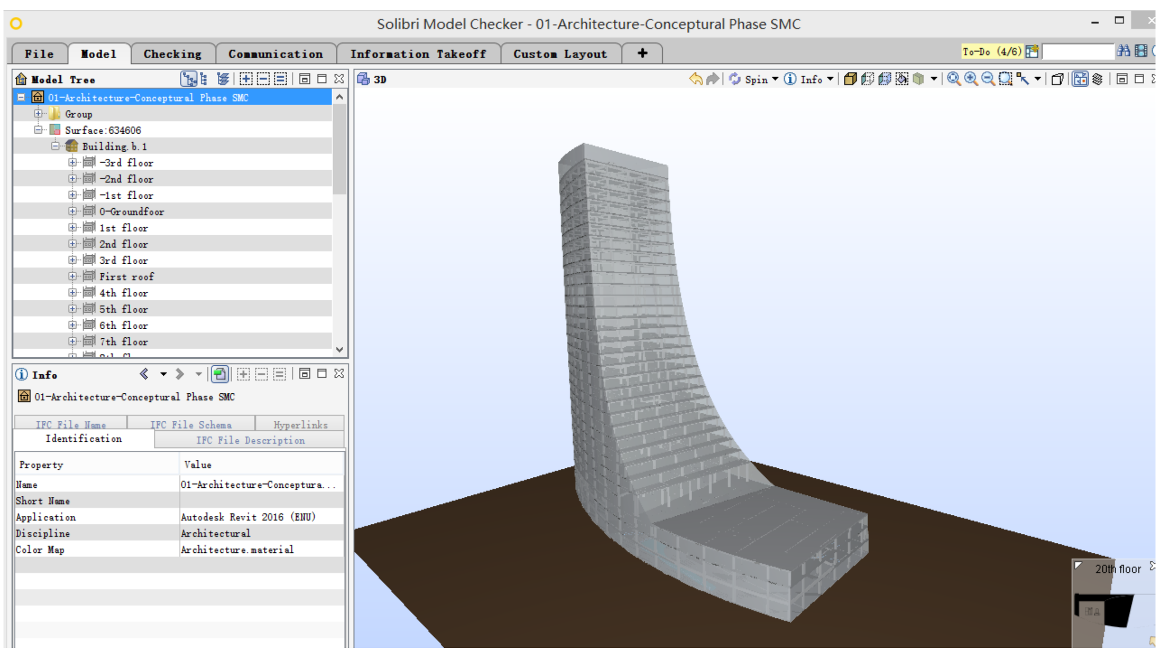


Figure 18. Model in SMC

- Rule-set management

In this case study, the purpose of model checking is to check the general modeling issues, for example BIM Validation for architectural model, components intersections, deficiency detections, general space checking etc. Therefore, the following rule-set structure is designed for conceptual phase model checking:

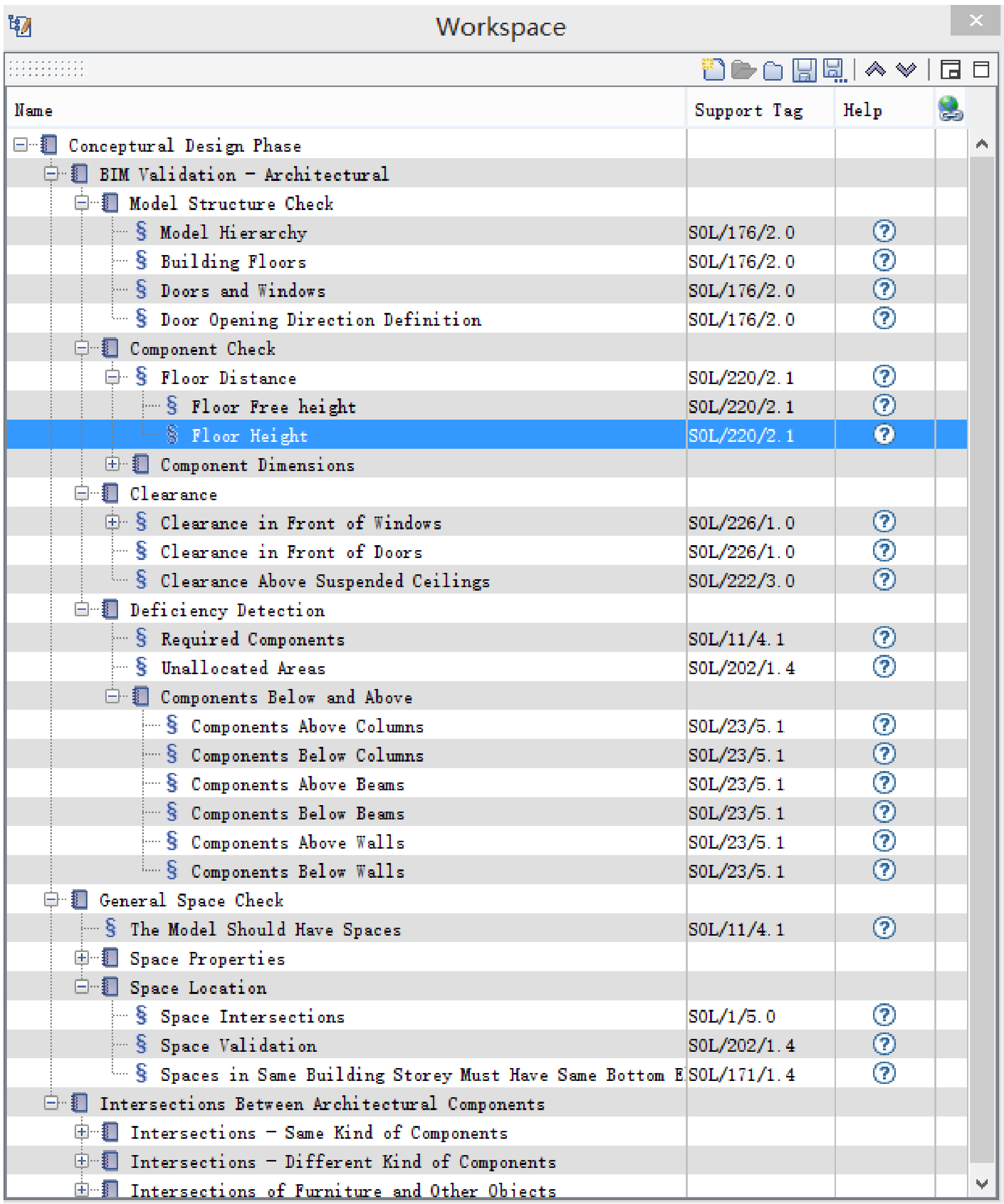


Figure 19. Rule-set Structure in SMC

During the rule-set management, rule interpretation is critical for a valid checking process. In this case, Chinese design code for office building JGJ67-2006 (zeng, et al., 2006) and Chinese fire protection regulation for high-rise buildings GB 50016-2014/GB50016-2006 (Zheng, et al., 2014)

(Li, et al., 2006) are used. For example, *"Item 3.1.11. The minimum clear height of office room is not less than 2.60m, with central air conditioning system should not less than 2.40m; The clear height of corridor is not less than 2.10m, the storage room is not less than 2.00m."* (zeng, et al., 2006) This rule is used to define the restraint of floor free height and floor height, that could be translated into machine-readable language as showed in figure 20 and figure 21:

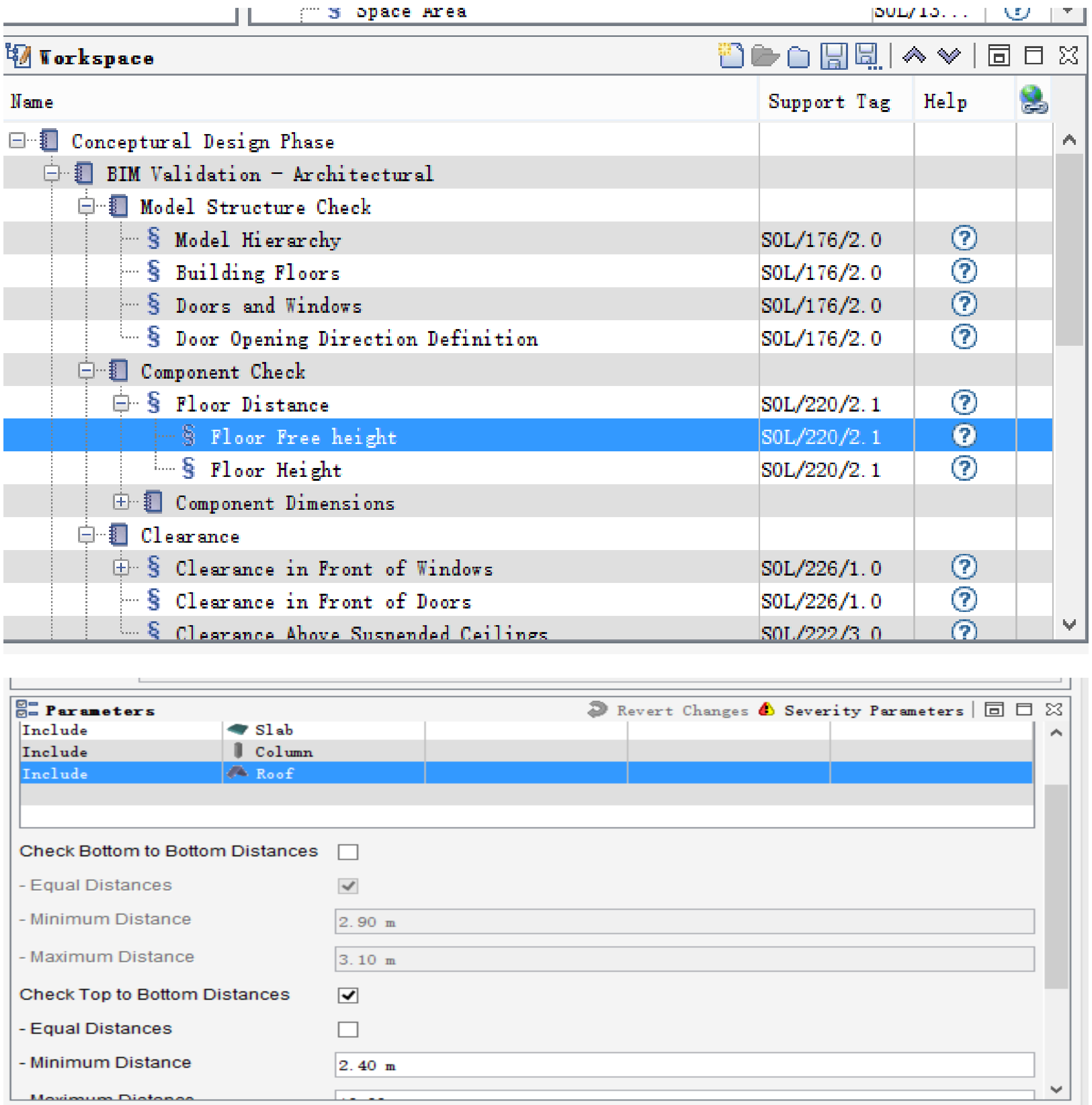


Figure 20. Floor free height limitation

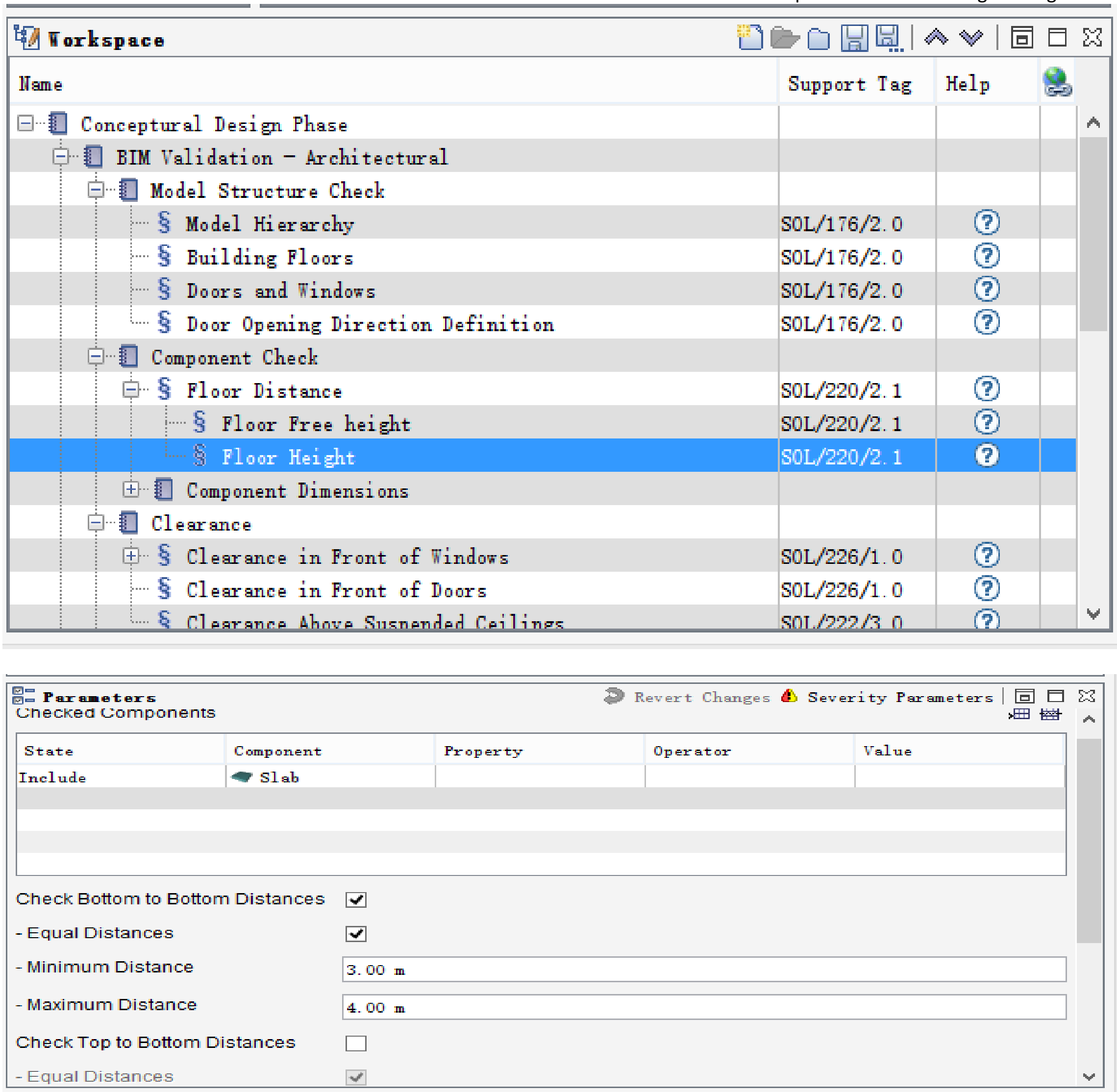


Figure 21. Floor height limitation

- **Rule execution**

Once the model is checked, the Checking Tree Table (Figure 22. Checking Tree Table) shows the status of each rule. The colored symbols on the right (Figure. 23) indicate respectively: Critical problem, Moderate and Low Severity; Rejected; passed.

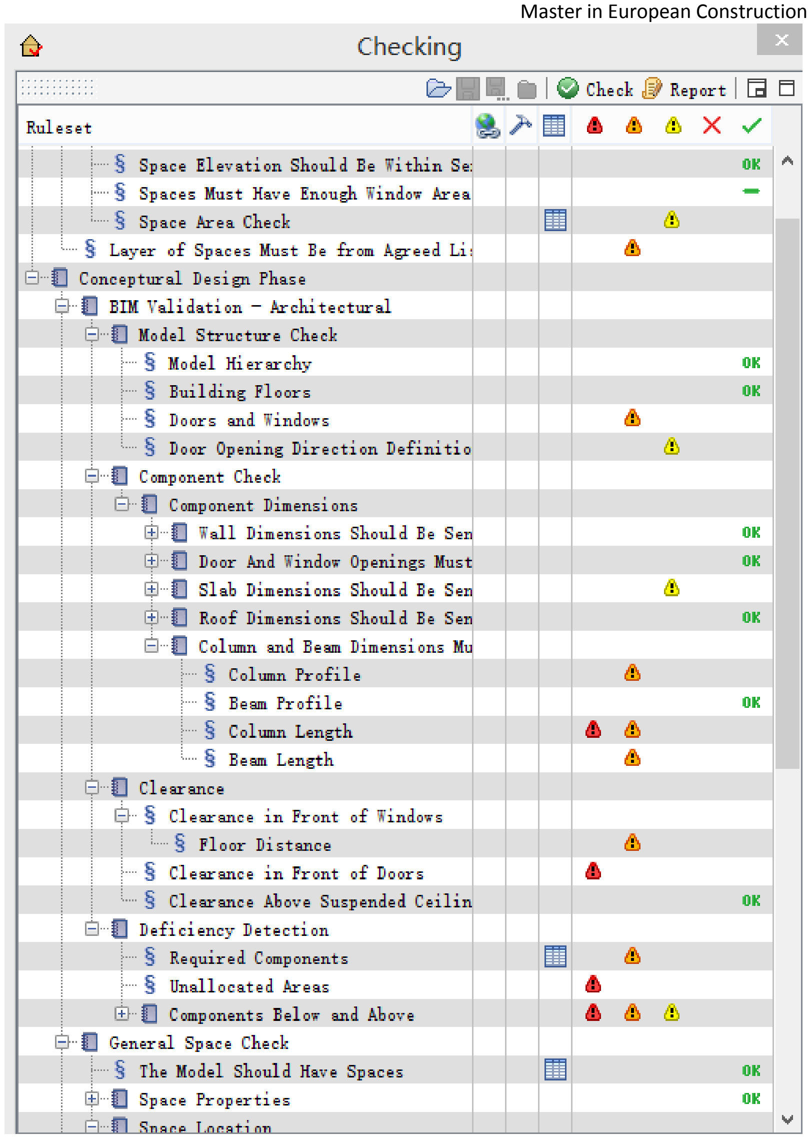


Figure 22. Checking Tree Table

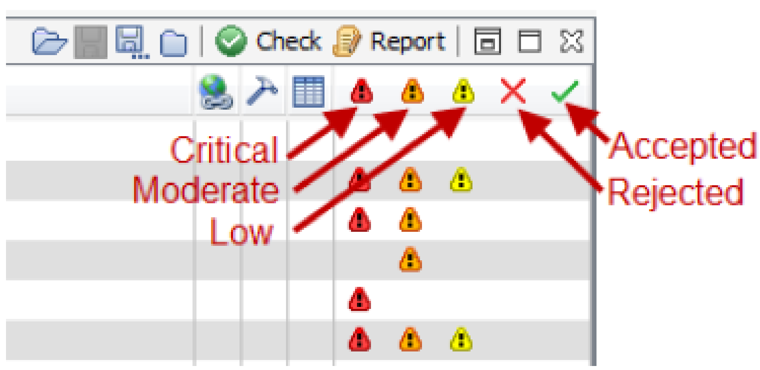


Figure 23. Signs of results

- **Rule check report**

In SMC, reports can be saved in Excel, PDF, RTF and BCF (.bcfZIP) formats. The complete report in Excel format can be found in Appendix 3 “Issue report for conceptual phase design”.

Based on the rule-set management structure, in this example, issues are mainly related with the Architecture model , intersection between component to component (ex. wall to wall intersection, wall to beam intersection, beam to slab intersection etc.), not enough clearance in front of a door or a window, components deficiency etc. For example:

ISSUE 1 Components intersection

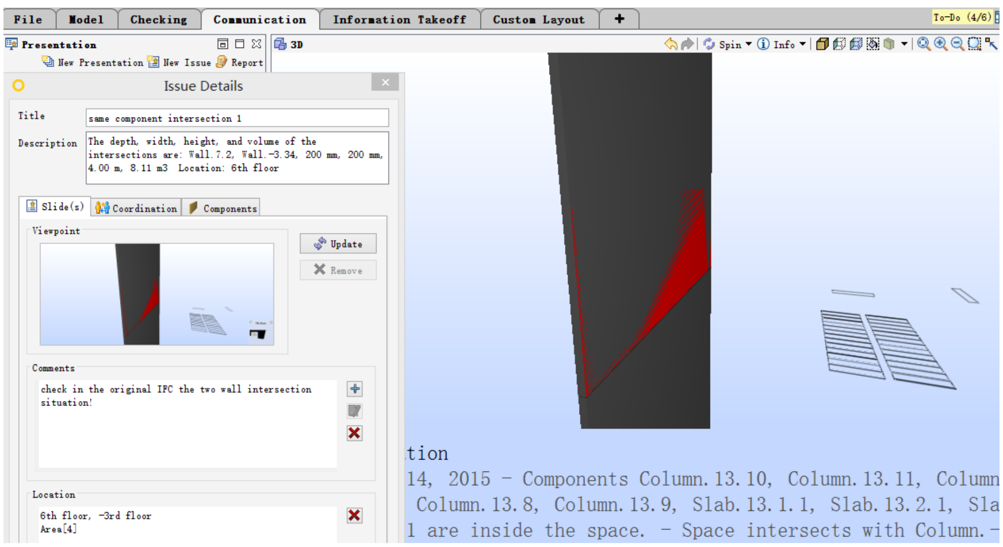


Figure 24. Wall to Wall intersection

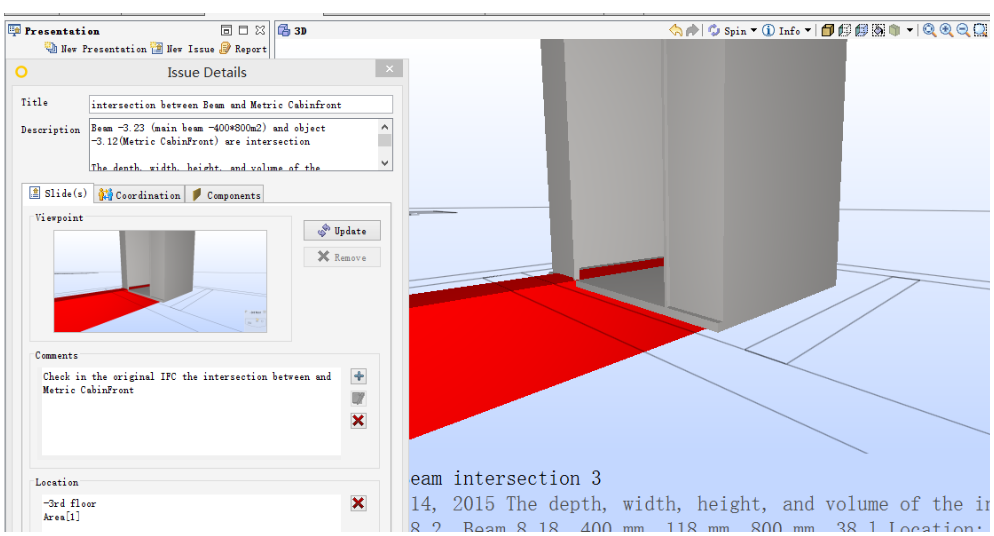


Figure 25. Beam to Metric CabinFront intersection

ISSUE2 Door Operation Direction

This rule "Door opening direction definition" (SOL/176/2.0) is used to check opening directions of doors. For example, in the Code of Design on Building Fire Protection and Prevention GB50016-2006 (Zheng, et al., 2014) (Li, et al., 2006) *"Item 5.5.3 "The door operation of evacuation door in each floor should open towards staircase, except on the ground floor evacuation door should open outwards"* and *Item 5.5.4 "Staircase should connect to the surface and doors shall open outwards."* In order to translate these paper written rules into machine language, "Accessibility Rule" checking would be used, while the correct definition of Door Opening direction is prerequisite for "Accessibility Rule" checking process.

The issue reports (see figure 26. Door opening direction results) flagged with the exclamation mark means that, there is no definition about the door opening direction in the imported IFC model. A manual check of the Revit (.ifc) model, it shows that, indeed, no operation type is defined (Figure 27).

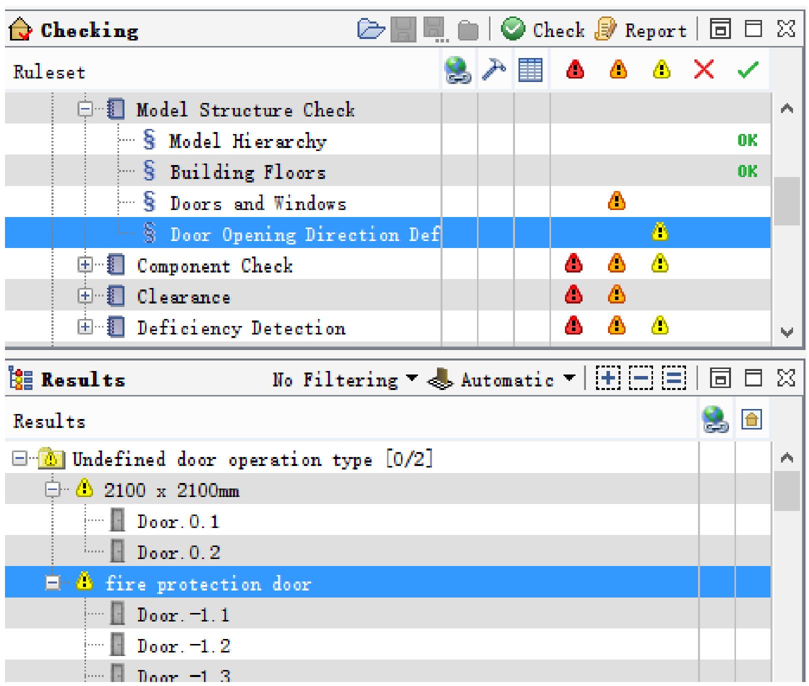


Figure 26. Door opening direction results

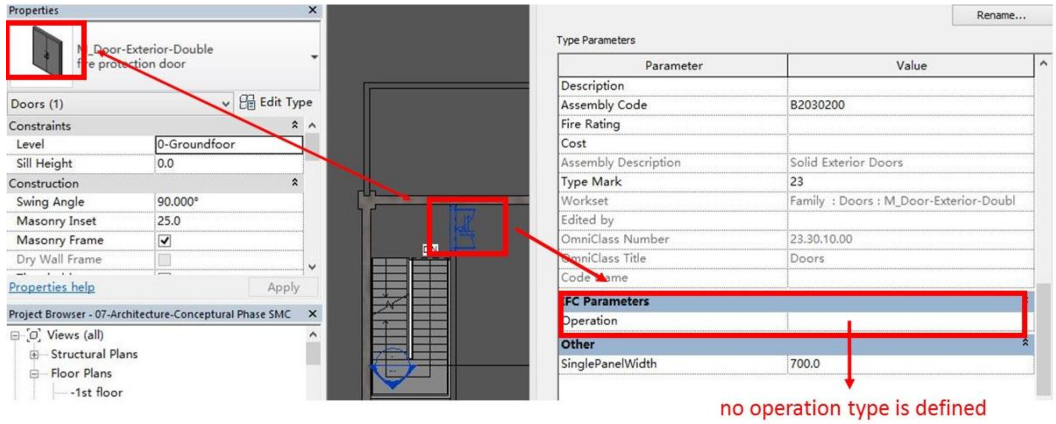


Figure 27. No operation type is defined in Revit (.ifc) model

ISSUE 3 Components above Beams

The rule "Components above beams" (SOL/23/5.1) is used to check that each beam touches slabs, roofs, columns or walls above itself. Here in the Results panel shows the issues (Figure 28. Components above beams):

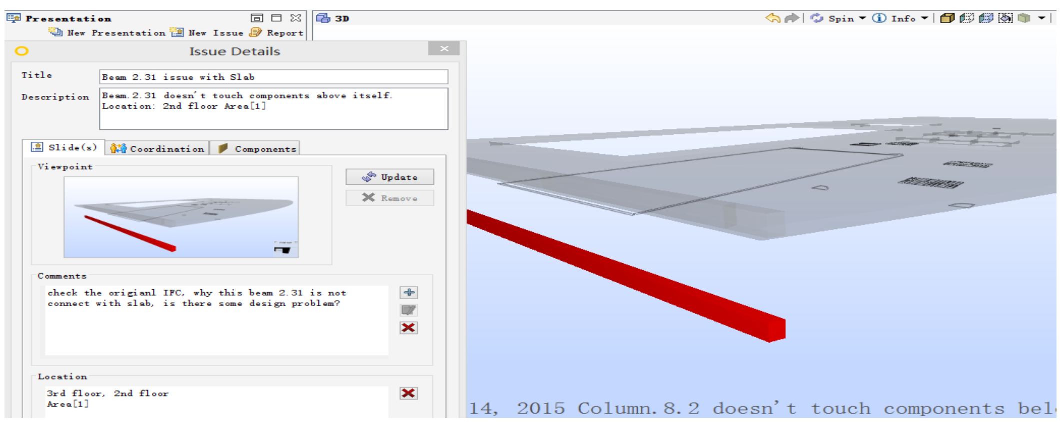


Figure 28. Components above beams

As a result, it shows that, beam 2.31 does not touch the slab above it, and it suspends. A visual inspection of the imported .ifc model reveals that, indeed, in the three-story-high hall, beams have no connection with above slab (Figure 29). Therefore, there must be some problems of the beam location in host model, which needs to be modified in the conceptual phase.

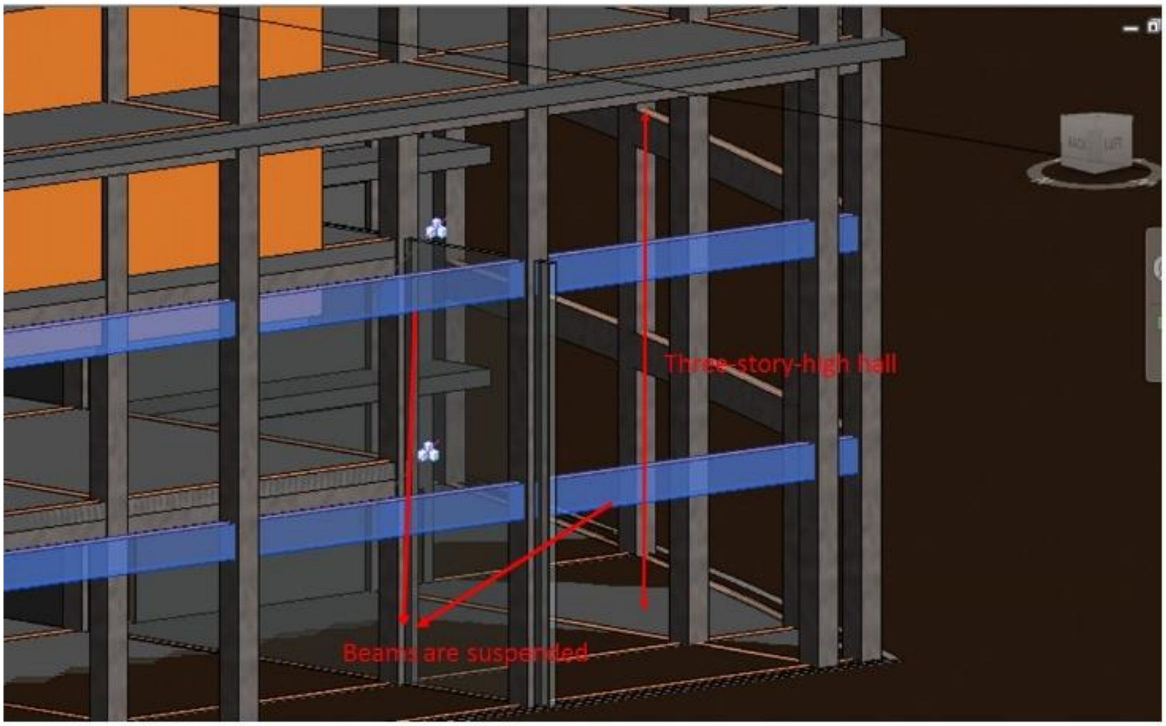


Figure 29. Revit model

(3).In Revit

In this step, we save issue report as BCF Report (.bcfzip) and open it in Revit with the Add-In called “BCFier” as shown in figure 30:

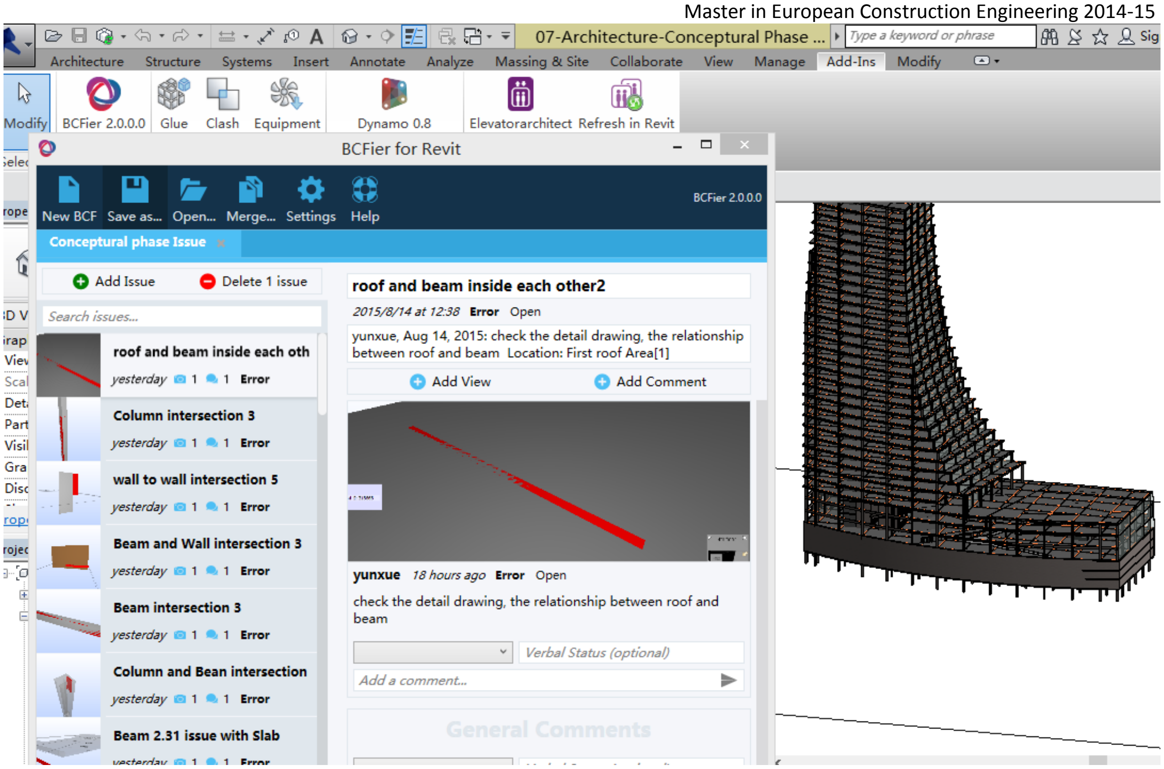


Figure 30. Open .bcfzip in Revit

By linking the bcfzip file in Revit, we can modify the model (.ifc) and make comments. For example, the first issue about components intersection (see figure 24. Wall to wall intersection), we could find the location of the issue directly using the bcfzip file, modify it and make comments. Steps are listed:

- Find the location of the issue (Figure 31)

We should do this step (Figure 31) every time when we are going to find the location of each issue before modifying them in the host model.

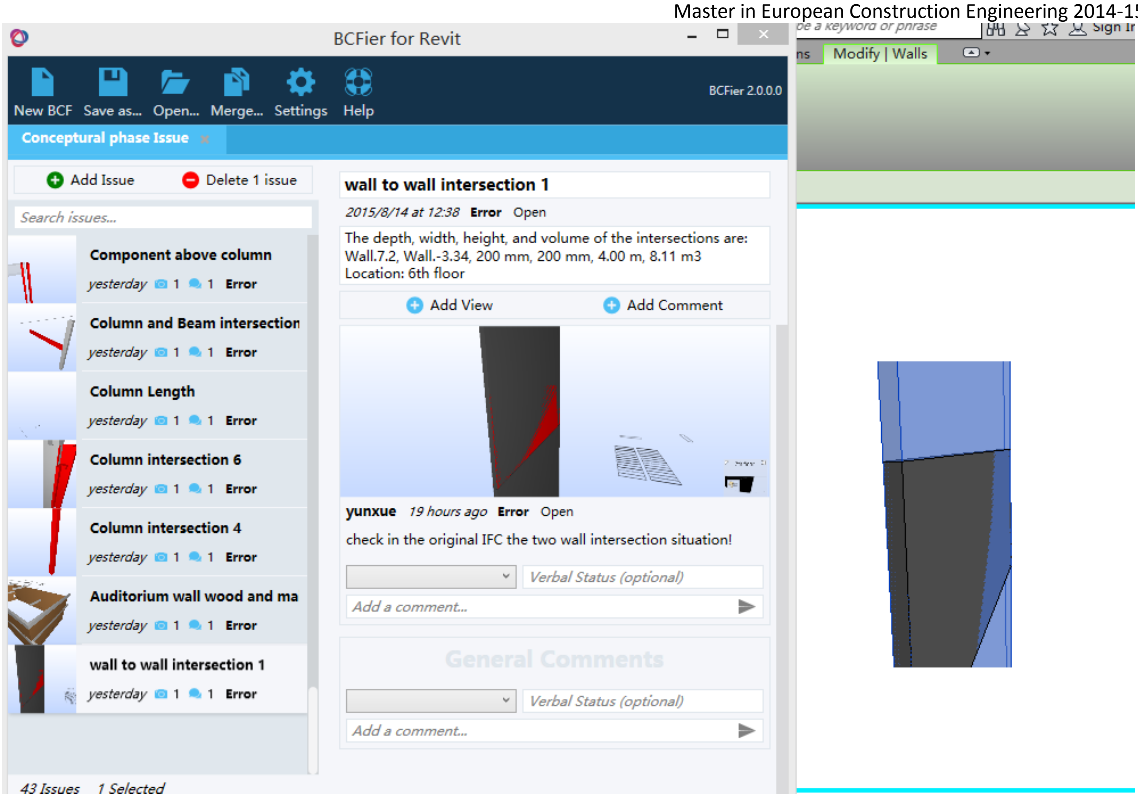


Figure 31. Find the location of the issue

- Modify the IFC model

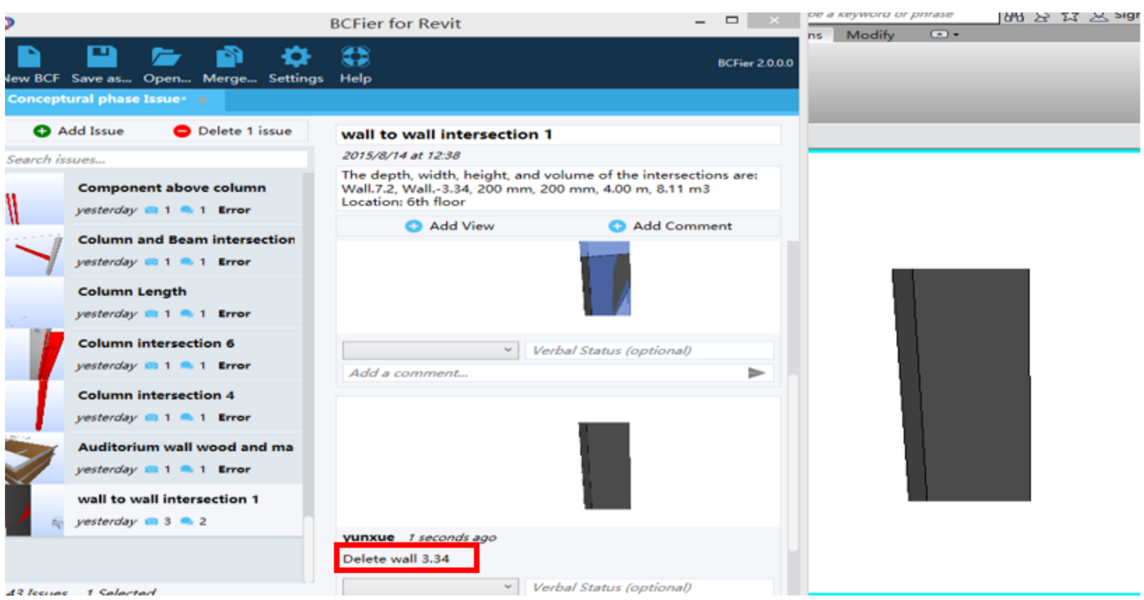


Figure 32. Modify issue in Revit

- Make comment

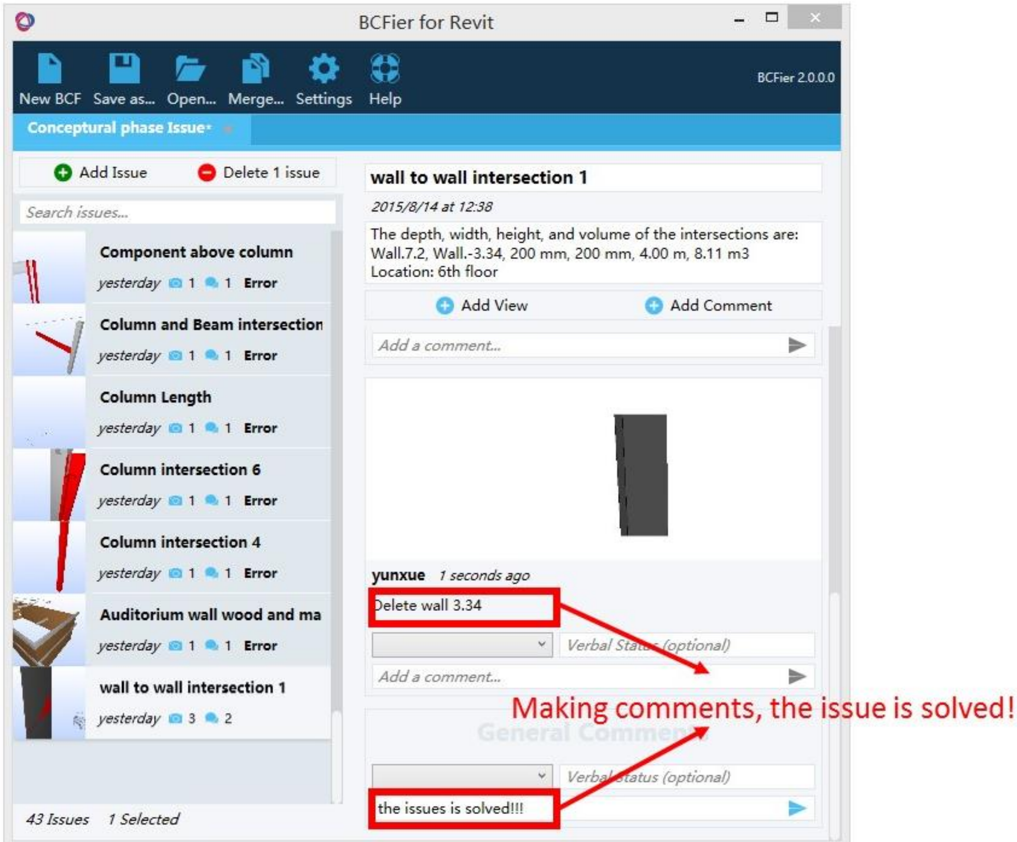


Figure 33. Make comments

(4).Recheck in SMC

After modifying all the issues involved issue BCF report in Revit, the model could be saved as .ifc and imported back into SMC for rechecking to see whether the issue is solved or not. If not, we could continue back to Step (3) until all the issues have passed.

4.2 Legal Design Phase

4.2.1. Model making in Revit

Automatic code-checking systems can be used during the legal code-checking phase before construction. In this case study, we continue to use the same case, namely high-rise office building with an LOD 300 model. With higher LOD, model becomes more complex, it hardly runs the whole model in the laptop, so we choose the floors from 10th to 20th as a sample to check with building codes, as shows in the following:

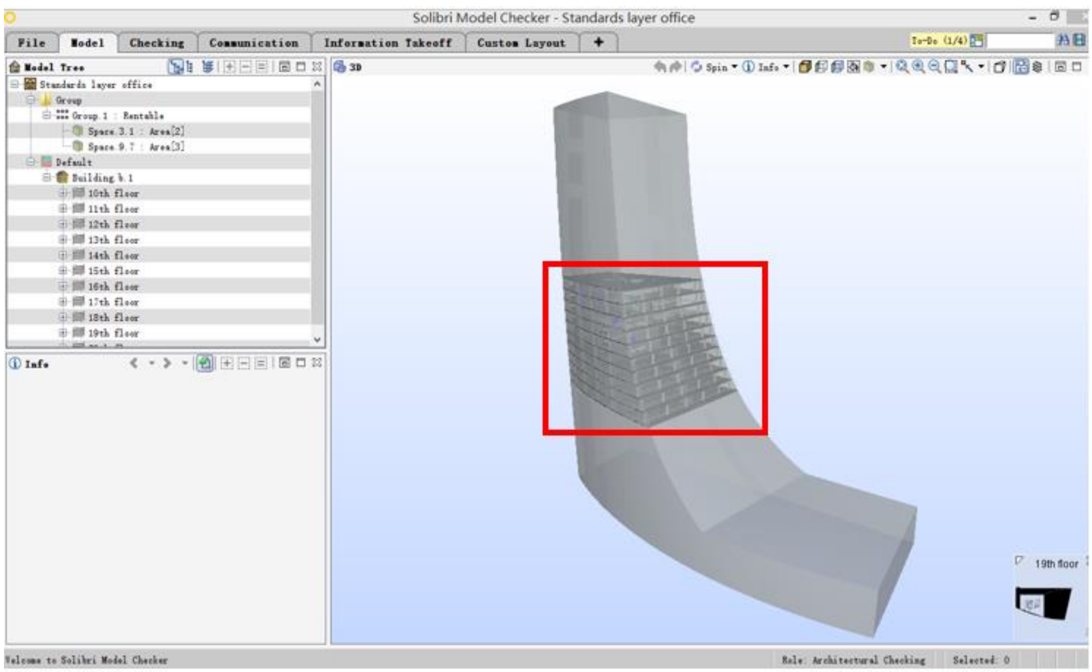


Figure 34. High-rise office building (10th to 20th floor) (in SMC)

Figure 35. High-rise office building with LOD 300 (in Revit)

Similar to case study 1, the checking process includes the following steps: developing the model in Revit and exporting to IFC file by the designer, importing IFC to be checked in SMC for checking process then exporting excel report for communication and producing BCF (.bcfzip) to be used for model modification. This process is done by those who work in the verifying entity. After that, the designers can modify the IFC model with the help of the BCF file, and make comments to communicate with other team members. The modified IFC file is then sent to the regulatory agency for rechecking until all issues have passed. The complete workflow is illustrated in figure 15, legal code checking phase.

Following this workflow, the rules used in this LOD 300 high-rise building model are from office building JGJ67-2006 (zeng, et al., 2006) and Chinese fire protection regulation for high-rise buildings GB 50016-2014/GB50016-2006 (Zheng, et al., 2014) (Li, et al., 2006). Here, examples are presented for checking the escape route rule, fire compartment rule, maximum fire compartment area limitations, component fire rate and so on, shows in figure 36.

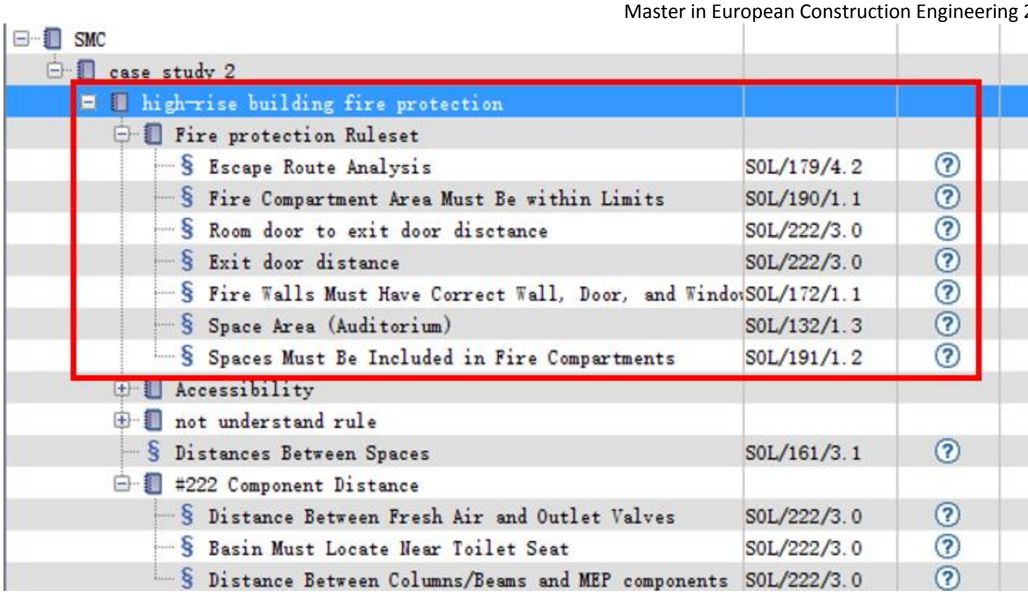


Figure 36. Rule-set structure

4.2.2. Rule checking examples

- **Rule fire compartment**

- **Rule interpretation**

Rules about fire compartment are defined in Table 2 (Li, et al., 2006).

Table 2. Fire separation area requirement:

	Class	*Max height/story*	*Max Separation Area (m2)*	*Remarks*
High-rise Civil building	*I*	*- Residential >54m - Public >50m Or any story S>1000m2*	*1500*	*For the stadium, the theater audience hall, the maximum of fire district may be increased*
	II	*Residential 54m>= x >27m*		
Single, multiple civil building	*I,II*	*Residential<=27m Single PB >24m OP <=24m*	*2500*	
	III	*5 F*	*1200*	-

	IV	*2 F*	*600*	*-*
Basement, semi-basement	*I*	*-*	*500*	*The maximum area of equipment room should be less than 1000m2*

Note: "When Sprinkler is set, the Max separation area double of the limitation area, namely 3000m2 for high-rise building."

In SMC, this paper-written code could be interpreted as figure 37

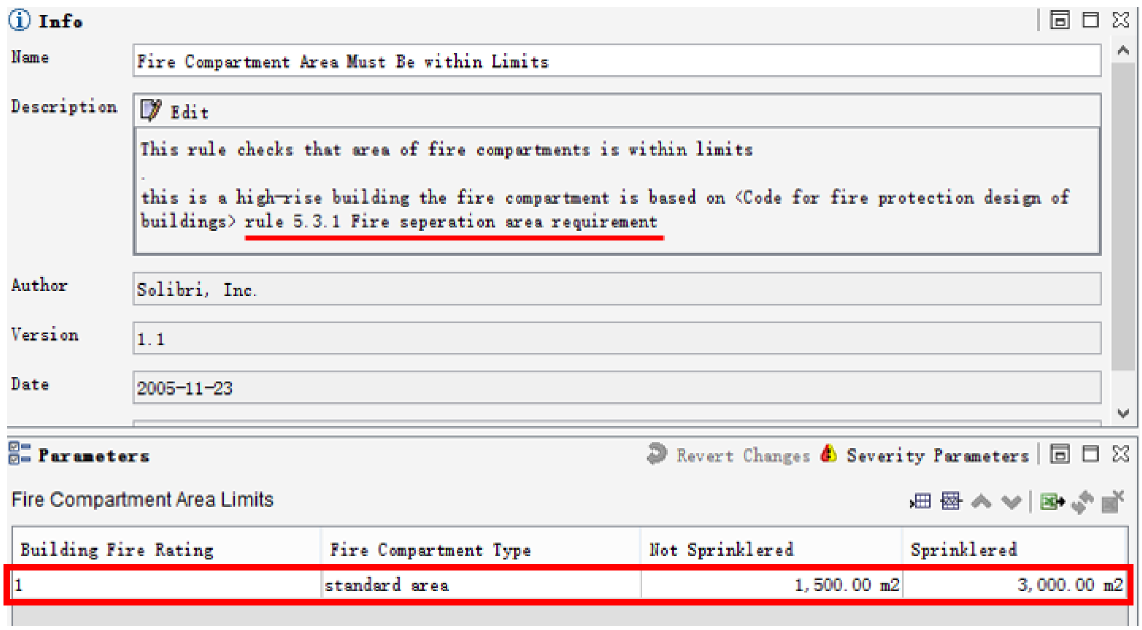


Figure 37. Fire compartment rule interpretation in SMC

- **Rule checking and reporting**

Figure 38 shows the checking results and the issues related with fire compartment list in Appendix 4 "Issue report of legal phase case study (Fire compartment rules)".

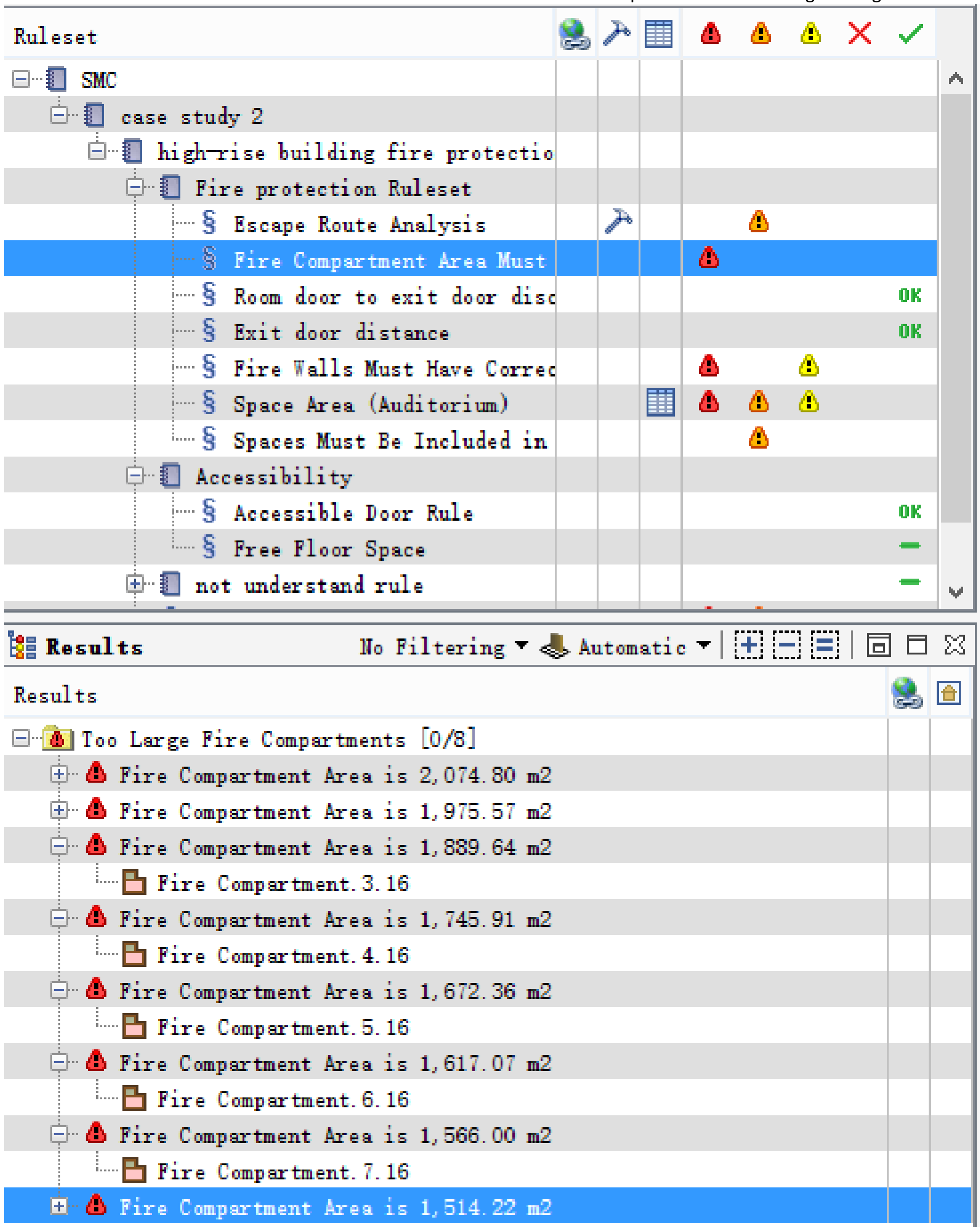


Figure 38. Checking results

- **Modify IFC model and make command**

As specified in rule *"item 5.3.1, the maximum for high-rise building in one fire compartment is 1500m2, if there are sprinklers, the maximum area is 3000m2."* There are two alternative ways to change the model. One way is to reduce the area in each fire compartment, so as to match the requirements (see figure 39). Another way is to define sprinklers in each fire compartment, so the maximum area will increase to double size, as illustrated in figure 40.

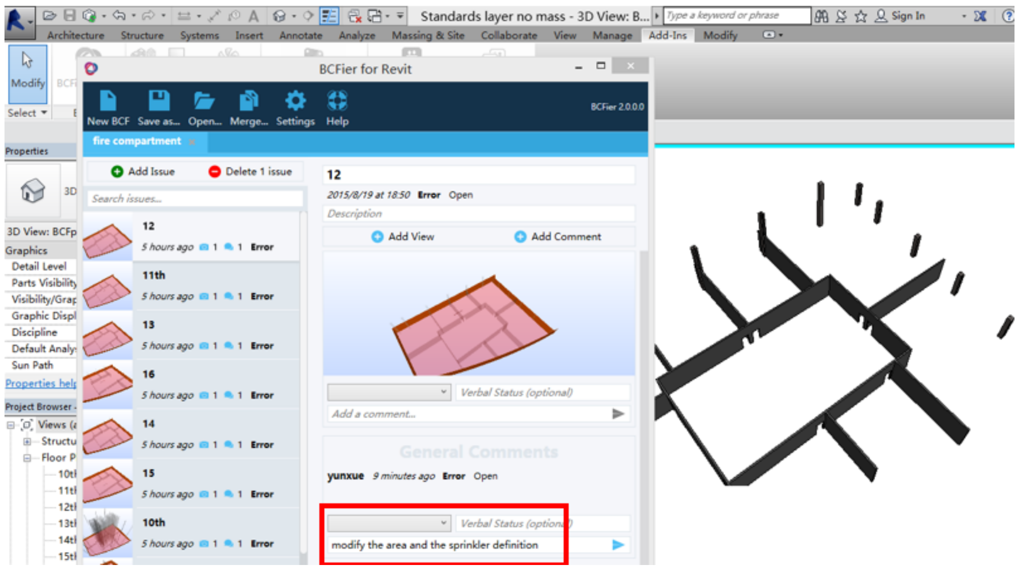


Figure 39. IFC modification and make commands

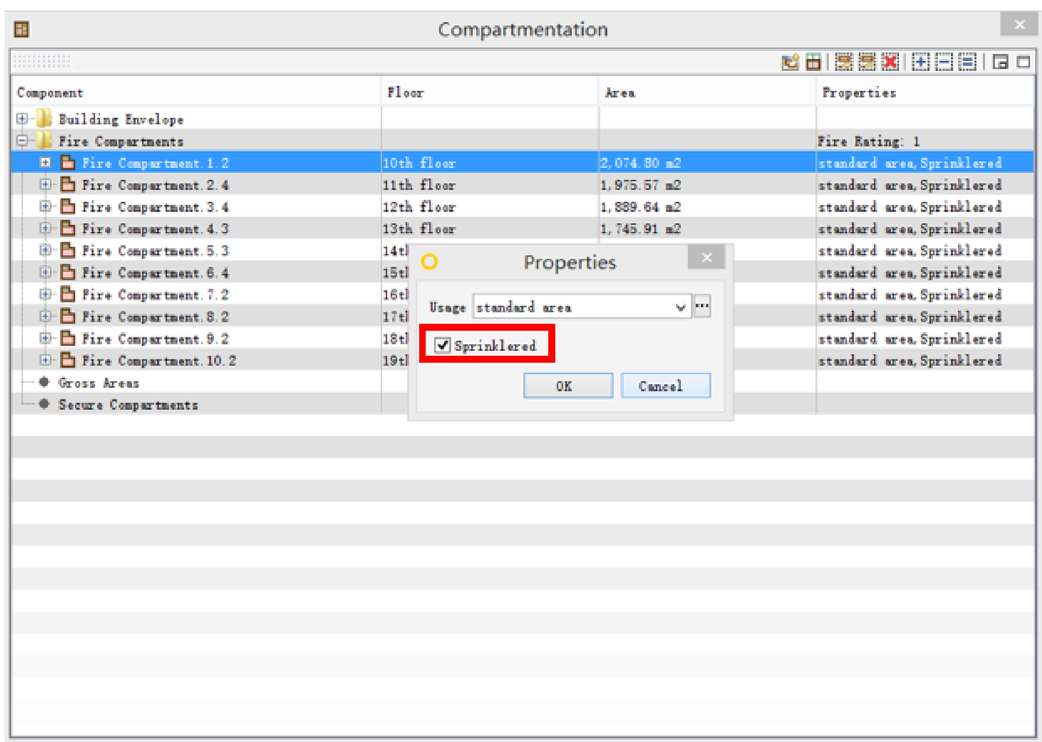


Figure 40. Define sprinkler in each fire compartment

- **Recheck in SMC**

After modifications, we import the new IFC file and check in SMC again, until this rule is passed (Figure 41).

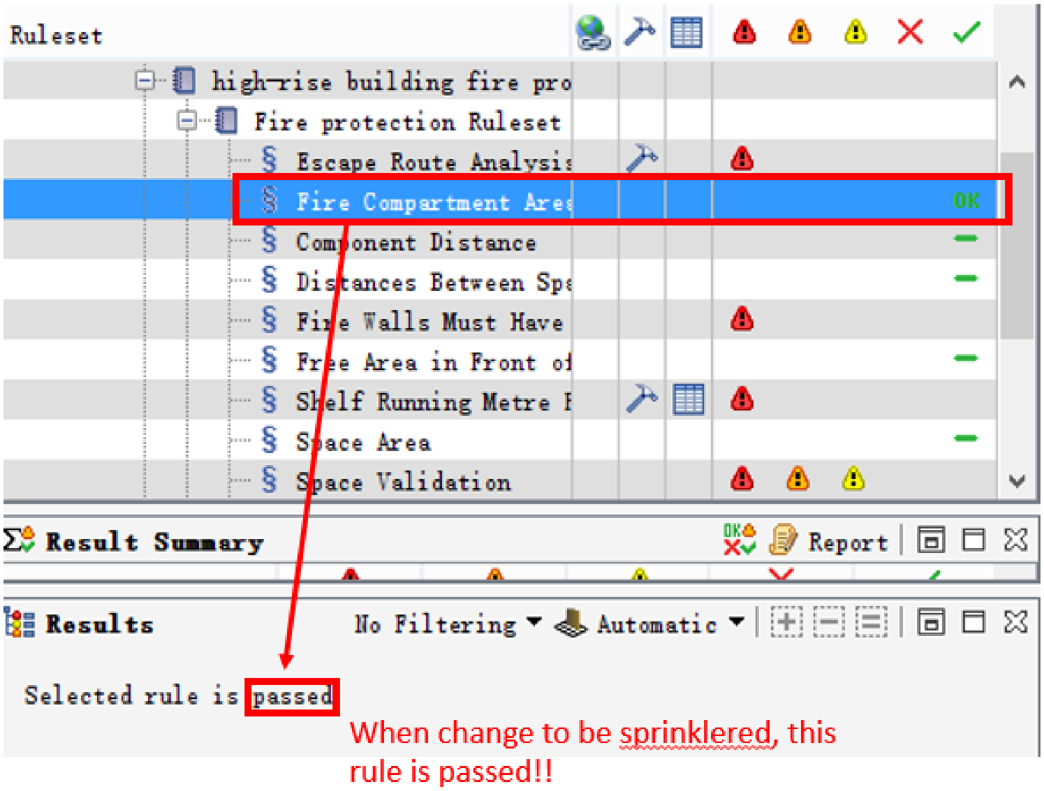


Figure 41. Recheck in SMC

- **Route distance rule**

There are two rules about the escape route distance in Chinese fire protection regulation for high-rise buildings GB 50016-2014/GB50016-2006 (Zheng, et al., 2014) (Li, et al., 2006) are important, namely

"item 5.3.8. The number of evacuation doors for rooms of the public building is not less than two and the distance between the nearest sides of two adjacent doors in a room shall not be less than 5m." and "item 5.3.13. The maximum distance from a room evacuation door to the nearest exit shows in table 5.3.13."

Table 5.3.13 the maximum distance from a room evacuation door that leads directly to the evacuation corridor to the nearest exit (m)

Building	The evacuation door between two exits	The evacuation door located on the two sides of a pecket-shaped corridor or at its extreme end
	Fire resistance class	Fire resistance class
	I & II	I & II
Nursery, kindergarten	25	20
Entertainment area	25	9

Hospital, sanitarium	Single, multiple		33	20
	High-rise	sickroom	24	12
		others	30	15
school	Single, multiple		35	22
	High-rise		30	15
Hotel, residential buildings, Exhibition space			30	15
others	Single, multiple		40	22
	High-rise		40	20

Table 3. The maximum distance from a room evacuation door that leads directly to the evacuation corridor to the nearest exit(m) (Li, et al., 2006)

- **Rule interpretation**

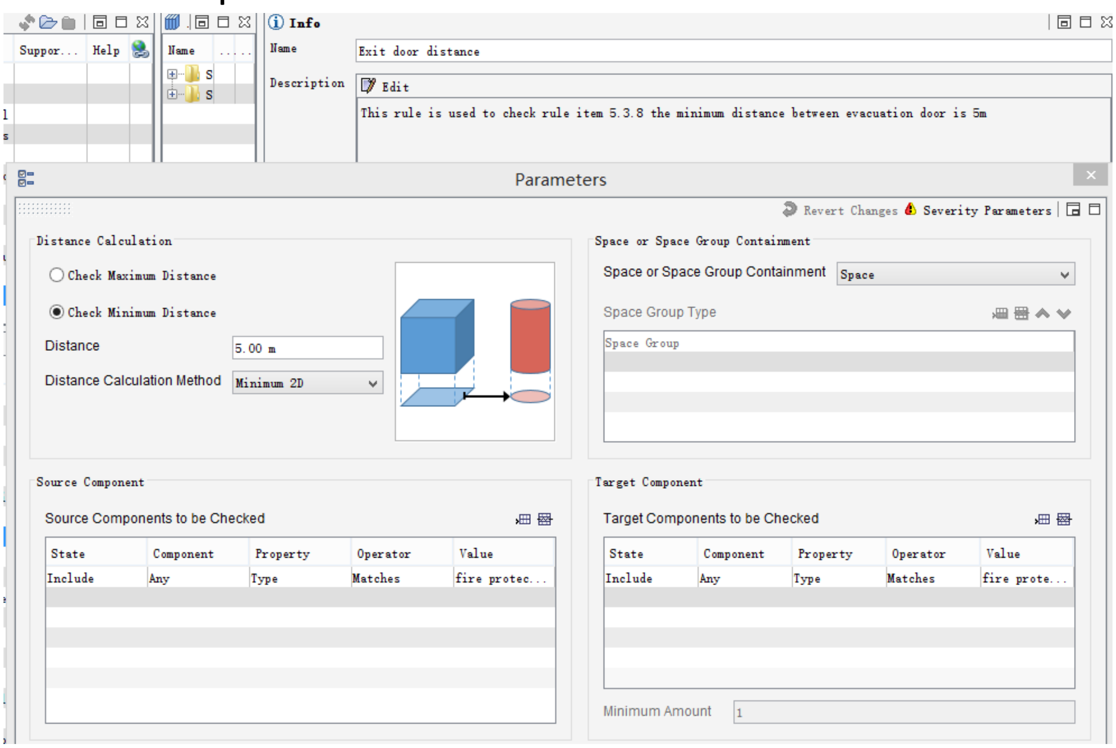


Figure 42. Code item 5.3.8 interpretation

The following figure 42 indicates rule item 5.3.8 are interpreted into SMC. The figure 43 shows item 5.3.13 interpretation (Zheng, et al., 2014) (Li, et al., 2006).

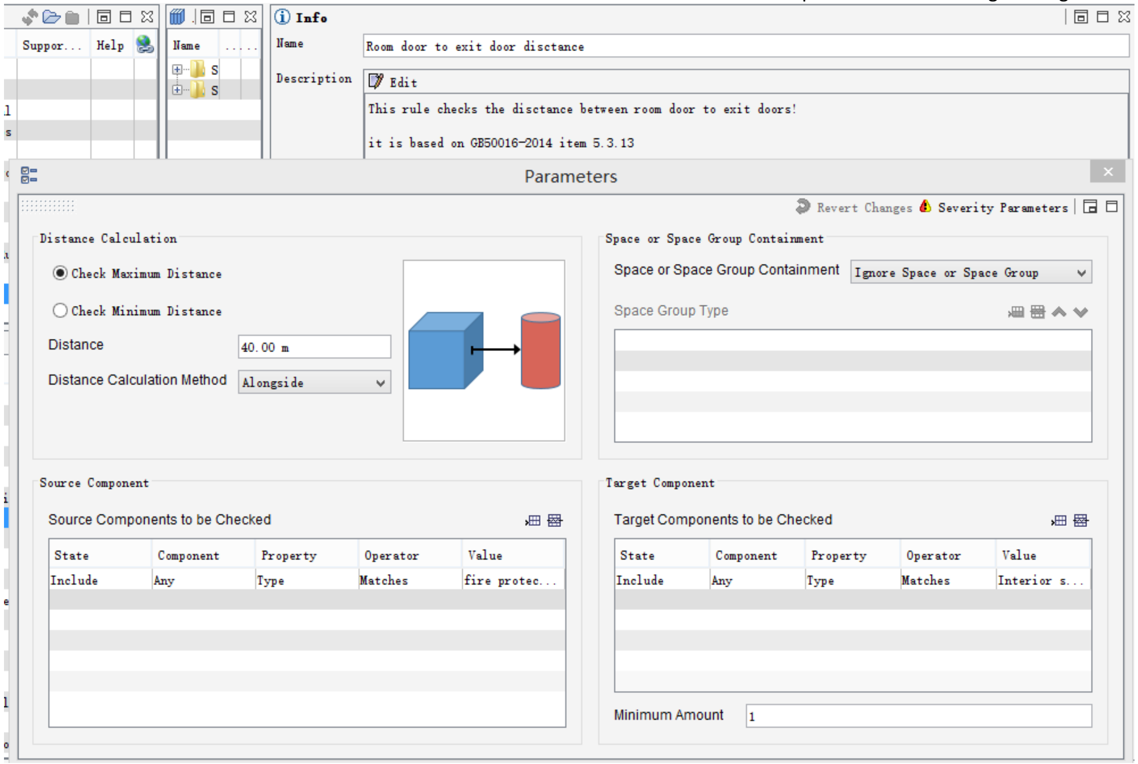


Figure 43. Code item 5.3.13 interpretation

- **Rule checking and reporting**

Figure 44 illustrates the checking process for item 5.3.8 and figure 45 for item 5.3.13 (Zheng, et al., 2014) (Li, et al., 2006).

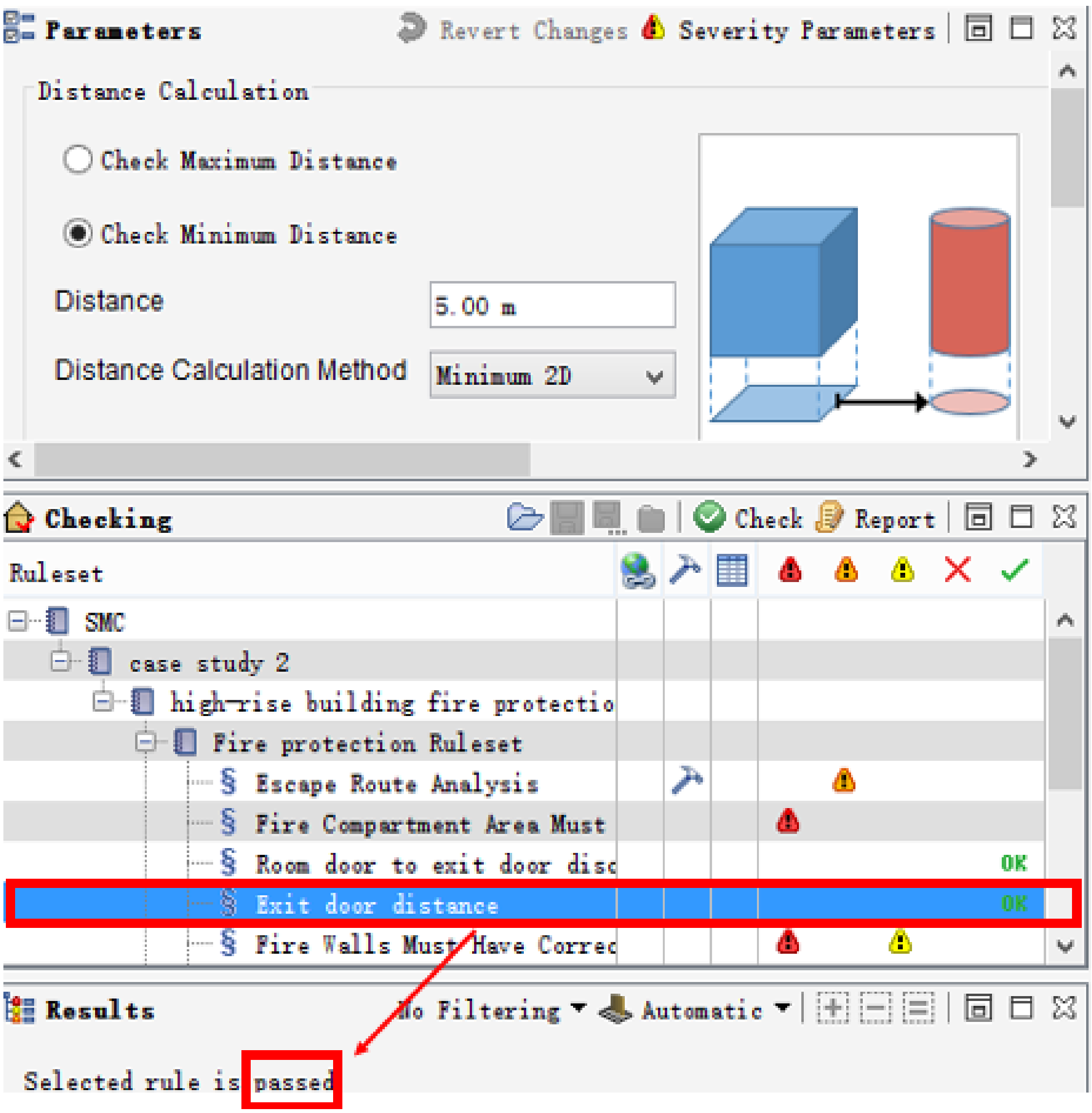


Figure 44. Code item 5.3.8 checking result

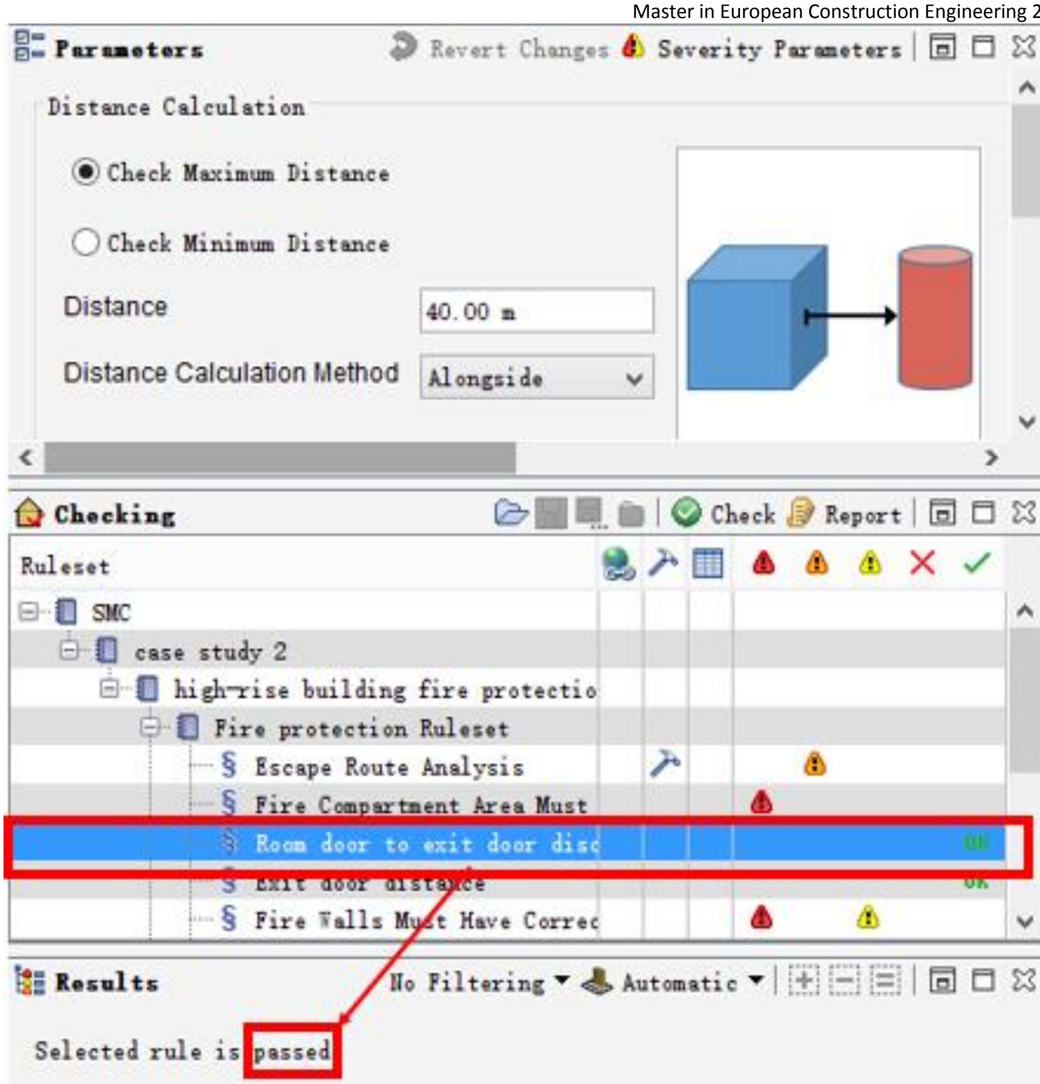
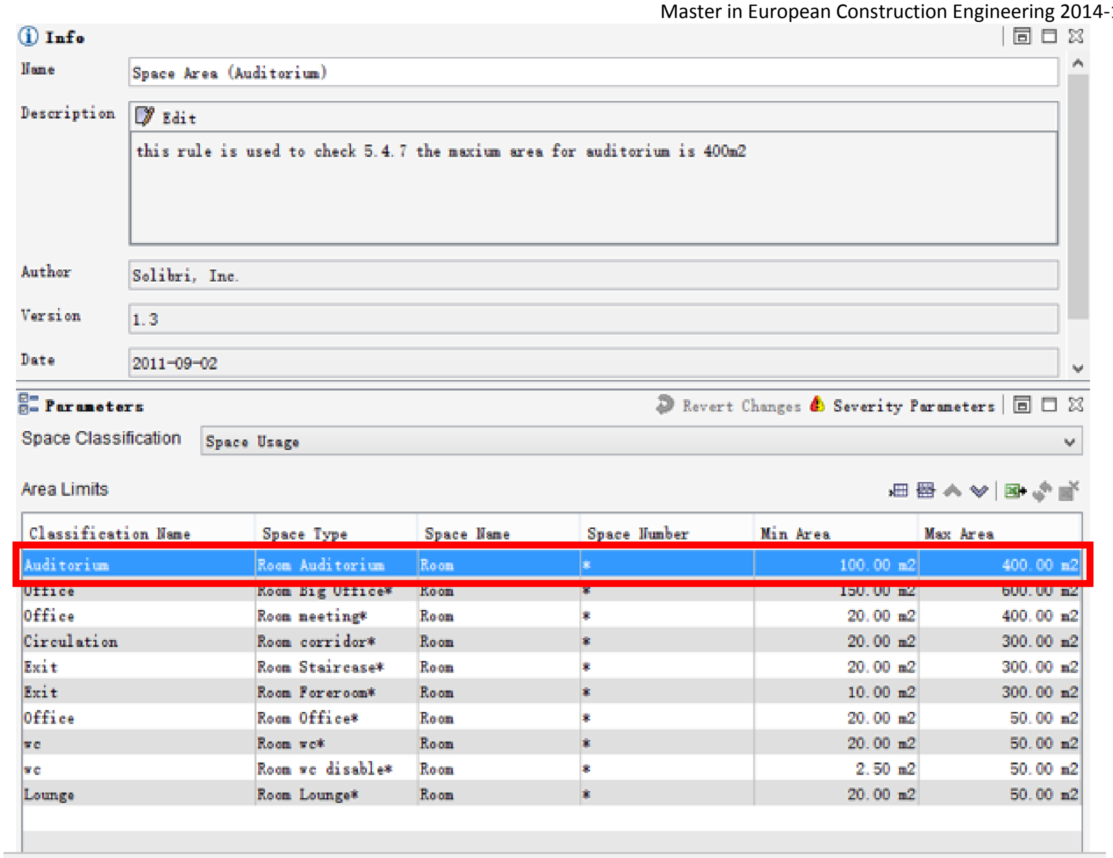


Figure 45. Code item 5.3.13 checking result

- **Room area requirements**

- **Rule interpretation**

"Item 5.4.7 requires that "Auditorium in high-rise building is better to be set in the ground floor, 1st floor, 2nd floor and 3rd floor, if it is higher than 3rd floor, the maximum area is less than 400m2 and must be not less than 2 exit door (Zheng, et al., 2014)." This room could be interpreted as shown in figure 46.



Classification Name	Space Type	Space Name	Space Number	Min Area	Max Area
Auditorium	Room Auditorium	Room	*	100.00 m2	400.00 m2
Office	Room Big Office*	Room	*	150.00 m2	600.00 m2
Office	Room meeting*	Room	*	20.00 m2	400.00 m2
Circulation	Room corridor*	Room	*	20.00 m2	300.00 m2
Exit	Room Staircase*	Room	*	20.00 m2	300.00 m2
Exit	Room Foreroom*	Room	*	10.00 m2	300.00 m2
Office	Room Office*	Room	*	20.00 m2	50.00 m2
wc	Room wc*	Room	*	20.00 m2	50.00 m2
wc	Room wc disable*	Room	*	2.50 m2	50.00 m2
Lounge	Room Lounge*	Room	*	20.00 m2	50.00 m2

Figure 46. Item 5.4.7 interpretation

- **Rule checking and reporting**

Figure 47 shows the checking result, and the all issues related with room area requirements are listed in Appendix 5 “Issue report of legal phase case study (Room area issue)”.

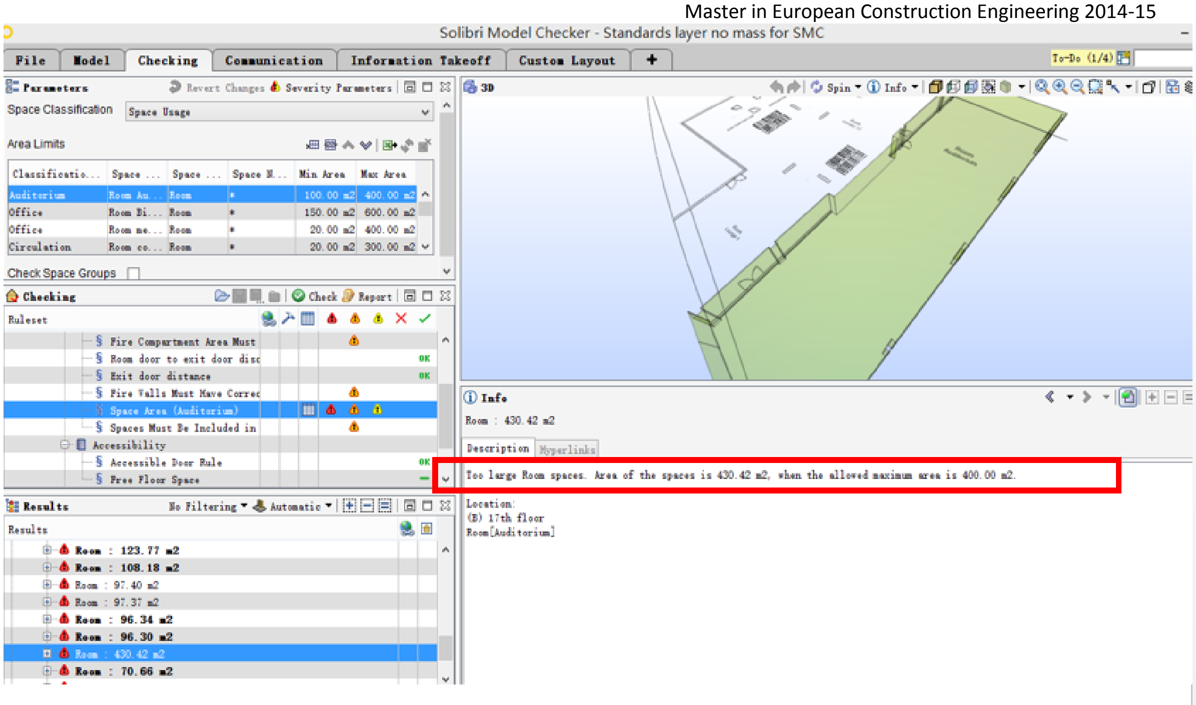


Figure 47. Auditorium maximum area checking result

- **Modify IFC model and make command**

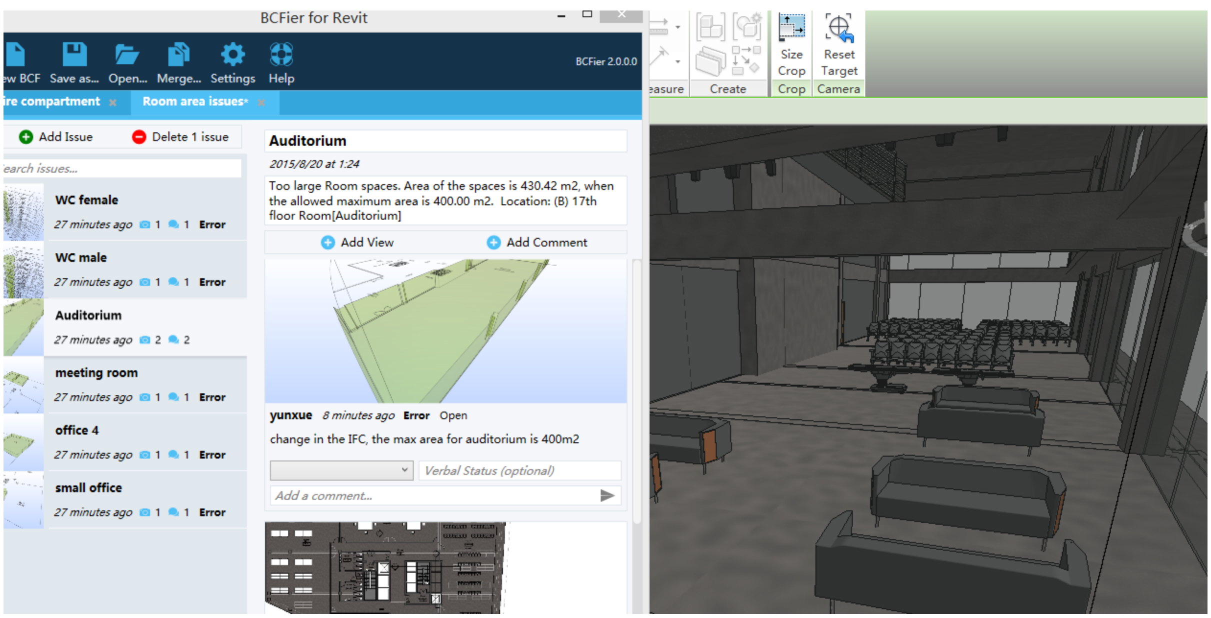


Figure 48. modification of Auditorium in Revit

In this case, the auditorium defined in the IFC file is divided in two in order to match the maximum area requirements specified in item 5.3.13 office building code (zeng, et al., 2006).

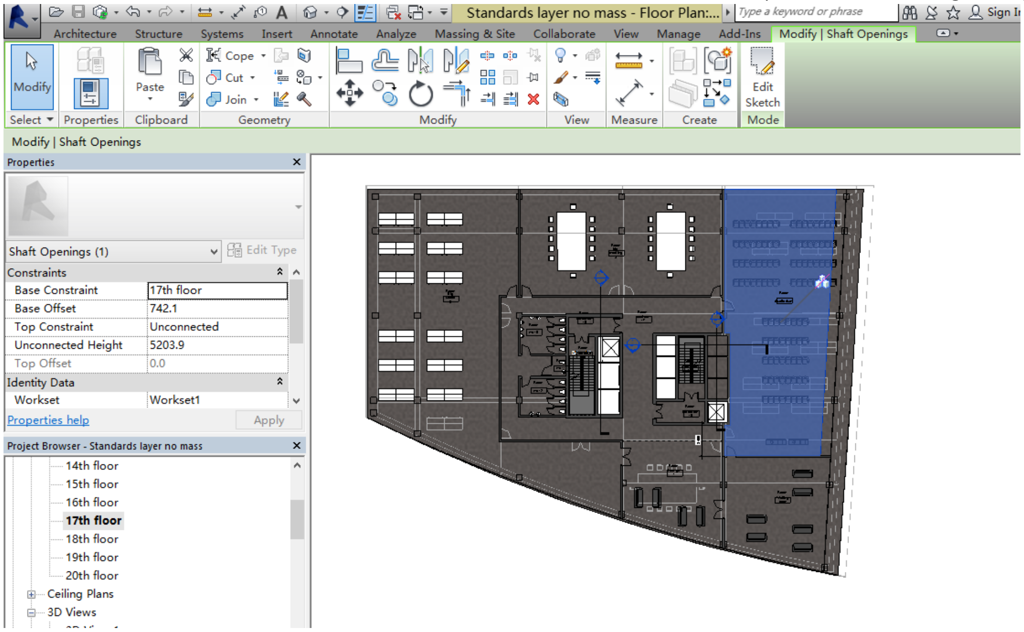


Figure 49. Modification of Auditorium in Revit

- **Recheck in SMC**

After modification, we import the new IFC file and check in SMC again, until this rule is passed.

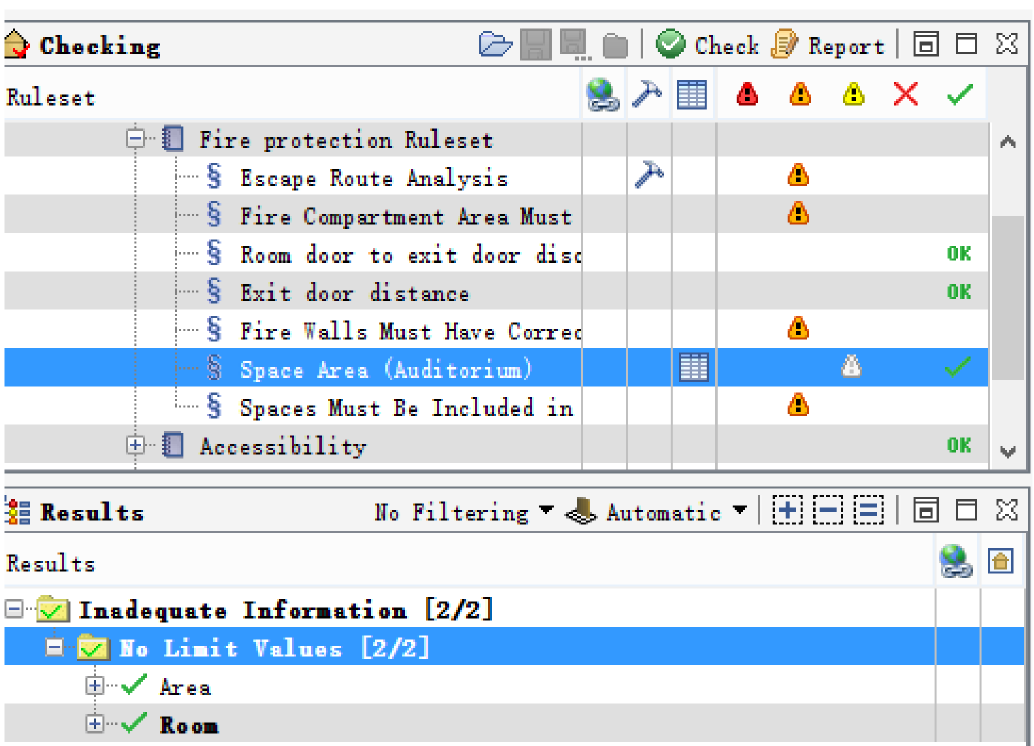


Figure 50. Recheck in SMC

4.2.3. Results report

In this case, building code about fire protection in high-rise building (Zheng, et al., 2014) (Li, et al., 2006) and office design code (zeng, et al., 2006) are used. All issues are included in a report presented in Appendix 4, Appendix 5 and Appendix 6.

CHAPTER 5 CONCLUSIONS

This paper reviews current initiatives with automatic code-checking systems. Based on the current efforts, the author proposed a workflow to combine the BIM modeling software and model checker application to complete the process from model development, to code checking to model update. In addition, case studies using a Chinese high-rise office building have been developed to present the workflow in practie. In addition, it is an advanced step to apply international model checking, Solibri, to a Chinese project for checking Chinese building regulations. Indeed, software needs to be thoroughly customizable to be adapted to different building codes and this is not a feature that is made available by existing application.

With the development of building information modelling, higher requirements of automatic code-checking system are emerging. It would be envisioned for a broad range of uses in the AEC industry during both conceptual and legal checking phases, for both designers and authorities in regulatory entities.

It is believed that the automatic code-checking workflow presented here will contribute to accelerate BIM implementation in an earlier stage. In addition, it stimulates more seamless and lossless interoperability between various software tools and among different stakeholders during BIM implementation.

The field of automatic code-checking is emerging, and it would continue to offer more help in the future, with BIM implementation from level 2 to level 3 stage. Although fully automated code-checking procedures are still many years away and the research in this area is still immature. It is currently possible to verify models for compliance with a significant portion of the regulations covered in this dissertation. Other rules are not verifiable due to limitations in available software tools, modeling development practices or in the nature of the rules themselves.

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CHAPTER 7 APPENDIX

Appendix 1. Building Code Classification of Chinese Residential building codes

Code for design of **residential buildings** GB 50096-2011 (Lin, et al., 2011)

NOTE:

When written as "Item X.X.X" is based on Code for design of residential buildings GB 50096-2011 (Lin, et al., 2011); written as "Item XXX" is based on China Building Code, as a supplementary code for Chinese residential buildings (Technology, Dec.2000).

1. Verifiable rules

Item 5.2.1. It is better not to connect each bedroom in one apartment. The bedroom area index is: bedrooms for double persons, 9m2; bedrooms for single person, 5m2. If the bedroom also acts as living room, it should be larger than 12m2.

5.2.2 Living room should be larger than 10 m2

Item 5.3.5 If all equipment is put one side, the clear width of the kitchen should be more than 1.5m. If on both side, the corresponding value should be larger than 0.9m.

Item 234. The kitchen having a small area and poor ventilation must use electricity or pipe gas and set up mechanical smoke exhaust equipment. The cooking range should have fire fight measures and its depth must larger than 0.5m.

Item 5.5.1 The residential building's story height should equal to or less than 2.80m.

Item 5.5.2 The clear heights for bedroom and living room should not less than 2.4m. Partial clear height should not lower than 2.1m and this partial area should smaller than 1/3 of the whole room area.

Item 5.5.3 If the bedroom has a slope roof, the clear height for half of this bedroom cannot less than 2.1m. It is better for the rest space to have a lowest clear height larger than 1.7m.

Item 5.5.4 Kitchen, bathroom, toilet clear height cannot be lower than 2.2m.

Item 5.5.5 For the squat-type toilet or bathroom, the distance from the position where person squats to the upper water-saver cannot be less than 1.9m.

Item 5.6.2 The design for balcony railing should prevent the children from climbing. The clearance among the vertical rods of the railing should not be more than 0.11 m. At the sector for setting the flowerpot, the measures to prevent dropping should be adopted.

Item 5.6.3 For the low rise (1-3 stories) and multi-rise (4-6 stories) buildings, the height of the balcony railing should not be less than 1.05 m; for the mid-high rise (7-9), high rise (10-30) buildings, the balcony railing should not be less than 1.1m.

Item 5.7.1 The clear width of the corridor to bedroom or living room is larger than 1m, the corresponding value to auxiliary rooms is larger than 0.9m.

Item 5.7.3 The stair clear width for indoor stairs cannot be less than 0.75m when one side of the stairs is empty, cannot be less than 0.9m when walls are on both sides, and stair handrail should be set at one side of the wall

Item 5.7.4 For the indoor stair, the stepping width cannot be less than 0.22m. Its height cannot be less than 0.20m. The clear width of fan-shape stairs at 0.25m from inside cannot be less than 0.22m.

Item 5.8.7 The minimum sizes for doorways indoors should conform to the followings:

Type	*Width of the doorway (m)*	*Height of the doorway (m)*
Building's outdoor	*1.20*	*2.00*
Apartment's outdoor	*1.00*	*2.00*
Living room' door	*0.90*	*2.00*
Bedroom's door	*0.90*	*2.00*
Kitchen's door	*0.80*	*2.00*
Bathroom' door	*0.70*	*2.00*
Balcony's door	*0.70*	*2.00*

Item 6.1.4 The width of the public stair step should not be less than 0.3 m; the height of the stair step should not be more than 0.15 m and not less than 0.10m; when the width of the step platform is more than 1.80m, the height of the handrail should not be less than 0.9 m.

Item 6.3.3 The clear width of the public stair landing should not be less than the clear width of the stair, and should not be less than 1.20 m.

Item 6.3.5 The clearance among the vertical rods of the public stair railings should not be more than 0.11 m. When the width of is more than 0.11 m, some measures that can prevent the children from climbing must be adopted.

Item 6.4.1 When the building has more than 7 stories, or the height, which is from the door floor of the residents living at the highest level to the first floor, is more than 16 m, the elevators should be installed.

3.1.7 For the high-rise building, which has more than 12 stories, there should be more than 2 elevators.

Item 6.4.6 The depth of the elevator lobby should not be less than the depth of the largest elevator car among all of the installed elevators and it should not less than 1.50m.

3.2.1 The height of the railing for the side corridor and inner courtyard should not be less than 1.05 m, and no less than 1.10 m for the mid-high or high-rise building. The design for the railing should prevent the children from climbing. The clearance among the vertical rods should be less than 0.11 m.

3.2.3 For the building in the cold area, the storm porch cold or the out-opening door preserving heat should be installed, and at the entrance or exit facing to the north, west directions, the out-opening door or other cold proof facilities should be used.

Item 6.9.3 When the basement and semi-basement are used for the storage room, bicycle garage, and equipment room, the clear height should not be less than 2 m.

3.3.1 For the building with more than 4 stories, the garbage chute should be installed.

Item 231. The kitchen's area should fit for the followings:

If the fuel is pipe gas or liquefied petroleum gas, kitchen's area should be larger than 3.5 m2.

If the fuel is improved coal, kitchen's area should be larger than 4 m2.

If the fuel is raw coal, kitchen's area should be larger than 4.5 m2.

If the fuel is firewood, kitchen's area should be larger than 5.5 m2.

Item 235. Kitchens should have outfacing or corridor-facing windows.

Item 237. The kitchen should have a pre-exhaust position in the upper part of the cooking range. Kitchens in cold areas should have ventilating duct or other ventilating measures.

2. Non-propositions

Item 251. Residential building designers should compute the average apartment area and used area factor. They should be computed as followings:

The average apartment area = total building area (m2)/ number of apartments

Used area factor = total used area (m2) / total building area (m2)

Item 252. The used area should be computed in the following way:

The used area indoors includes bedroom, living room, transition, corridor, kitchen, bathroom, toilet, store space and closet.

For the apartment that has more than one story, all the areas of its indoor stairs should be added into the used area.

The chimney, ventilating duct and pipe that are not included in the construction area should be included in the used area.

3. Ambiguities

Item 222. Bedrooms should have daylighting and natural ventilation. When the bedroom is lighted through corridor, it should have good ventilation, safety and privacy.

Item 232. Kitchens should have cooking range, washing pool, chopping board place and fixed built-in closet. If not, there should have enough space for these things.

Item 223. Living rooms should have daylighting and natural ventilation. Its area may not be smaller than 10m2.

Item 5.2.4 Corridors and Dining room could have indirect lighting. Its area may not be smaller than 10m2.

Item 5.5.3 If the bedroom has a slope roof, the clear height for half of this bedroom cannot less than 2.1m. It is better for the rest space to have a lowest clear height larger than 1.7m.

Item 6.3.5 The clearance among the vertical rods of the public stair railings should not be more than 0.11 m. When the width of is more than 0.11 m, some measures that can prevent the children from climbing must be adopted.

Item 6.9.7 For the basement and semi-basement, some measures, such as water prevention, damp prevention, and ventilation, might be adopted. For the light shaft, the facilities, which can prevent the rainwater entering and can drain the water, should be installed.

Item 263. It is better for the rest space to have a lowest clear height larger than 1.7m.

Item 281. The size of turning corridor should be suitable for moving furniture.

3.2.4 When the public entrance and exit of the building are under the balcony or the side corridor, some safety measures should be adopted.

3.3.4 The material used for the garbage hopper might be corrosion resisting. The hopper door should be tightly closed automatically. The garbage exit might be installed for every floor. For the high-rise building, the trash closet might be installed.

4.1.5 In the areas of cold, warm, and hot weather, if the residence faces to the west, the sunshade method might be used for the exterior windows of the bedroom and living room.

4.1.4 The elevator hoistway might not be installed close to the bedroom or living room; the elevator machine room might be installed neither above the bedroom and living room, nor close to them. However, if it had be installed due to the plane layout, some measures, such as sound insulation and shock absorption, should be adopted.

5.2.4 It is better to design kitchen near to the access of the house.

5.6.1 It is better to have balcony or terrace

4. Others

Item. 244. The bathroom and toilet without ventilating windows must have ventilating duct. The air inlet and exhaust should be well designed.

Item 275. The equipment for drying clothes should be installed. For the balcony at the top floor, the rain cover should be installed. When the balcony connects the units, the dividing board should be installed.

5.4.1 For a bathroom, a toilet; a Washbasin and a bath device are three necessary sanitary equipment. Meanwhile the area of the bathroom should more than 2.5 m2

Item 282. Each apartment should have store space. The clear height of hung closet cannot be less than 0.35m. It is better that the clear depth of the closet is larger than 0.45m. For closets near to out wall, bathroom or toilet, the measures of moisture-proof and condensation-proof should be used inside.

4.2.4 There should be 2 sockets in the living room and bedroom individually, and one socket in the kitchen, bathroom, and entrance hall individually. The three-hole socket with single-phase must be used.

Appendix 2

Building Code Classification of Chinese fire protection building codes

Chinese fire protection regulation for high-rise buildings GB 50016-2014;Code of Design on Building Fire Protection and Prevention GB50016-2006 (Zheng, et al., 2014) (Li, et al., 2006)

1. Verifiable rules

5.1.11 Fire compartments shall be separated by fire walls. Fire shutters may be installed if it is difficult to use fire walls. The use of fire roller shutters shall meet the requirements of 7.5.3.

5.3.1 Fire separation area requirement

	Class	Max height/story	Max Separation Area (M2)	Remarks
High-rise Civil building	I	- Residential >54m - Public >50m Or any story S>1000m2	1500	For the stadium, the theater audience hall, the maximum of fire district may be increased
	II	Residential 54m>= x >27m		
Single, multiple civil building	I,II	Residential<=27m Single PB >24m OP <=24m	2500	
	III	5 F	1200	-
	IV	2 F	600	-
Basement, semi-basement	I	-	500	The maximum area of equipment room should be less than 1000m2

Note: If sprinkler is set, the maximum area is double size as list in table 5.3.1.

5.3.1 The exits of civil buildings shall be arranged separately. The horizontal distance between the nearest sides of two adjacent exits in each fire compartment or each floor of the same fire compartment shall less than 5m.

5.3.2 The exits of public buildings in each fire compartment or each floor of the same fire compartment shall be designed according to calculation, and shall not be less than two. One safety exit or evacuation stair is permitted if one of the following requirements is met:

- A single-story public building (expect nursery and kindergarten) with building area not more than 200 m2 and the occupants not more than 50;

- Public buildings with two or three stories (except hospital, sanitarium, building for the aged, children's activity room like children's studying room and playroom in the nursery and kindergarten etc.) that meet the requirements of Table 5.3.2.

Table 5.3.2 Conditions for providing one evacuation stair for public buildings

Fire resistance class	*Maximum permitted stories*	*Maximum permitted building area of each floor (m2)*	*occupants*
Class I,II	*3*	*500*	*The total occupants of the second and third floor are not more than 100*
Class III	*3*	*200*	*The total occupants of the second and third floor are not more than 50*
Class IV	*2*	*200*	*The occupants of the second floor are not more than 30*

5.3.8 The number of evacuation doors for rooms of the public building and the habitation building not for residential use with shared corridor shall be designed according to calculation and not be less than two. The distance between the nearest sides of two adjacent doors in a room shall not be less than 5m. If one of the following requirements is met, one evacuation door is permitted:

- The building area of a room is not more than 120m2. The door's net width is not less than 0.9m and the room is between two exits;

- A room (not of child-care center and kindergarten, buildings for the aged) is located at the extreme end of a corridor, the straight distance from the farthest point in the room to its evacuation door is not more than 15m, and the net width of the door is not less than 1.4m;

- Places used for singing, dancing, amusement and entertainment etc. with building area not more than 50m2.

5.3.11 The exits of any floor of the residential building unit shall not be less than two if the building area of one floor of the building is more than 650m2 or the distance between the outer door of one apartment and the exit is more than 15m. The design of staircase for residential building shall meet the following requirements:

- Closed staircase shall be designed if there are more than two stories in habitation building with shared corridor. Closed staircase may not be used if the entrance door of each unit is Class B fire door;

- Closed staircase shall be designed if there are more than six stories or each floor area is more than 500m2. Closed staircase may not be used if the door of each unit or the door and window opening to the corridor or staircase is Class B fire door or window.

5.3.12 The staircase of residential building should be designed with an exit leading to the roof. The door of the exit or the window opening to the roof shall be opened to the outside direction.

5.3.14 The net width of exit and evacuation door shall not be less than 0.9m. The net width of evacuation corridor and evacuation staircase shall not be less than 1.1m. If an apartment building with less than six stories, the minimum width of evacuation stair could not less than 1m.

5.3.16 For the public assembly buildings, such as theater, cinema, auditorium and stadium etc, the respective total width of the evacuation corridors, evacuation staircase, evacuation doors and exits shall be designed according to the number of the occupants and the index of net evacuation width, and the following requirements shall be met: The net width of the evacuation corridor in the auditorium shall be calculated on the basis of no less than 0.6m per 100 occupants, and the minimum net width shall not be less than 1m, the side aisle should not be less than 0.8m; The Table 5.3.16-1 shows the minimum net evacuation width per 100 occupants of building such as theater, cinema and auditorium etc. (m)

Table 5.3.16-1 The minimum net evacuation width per 100 occupants of buildings such as theater, cinema and auditorium etc. (m)

Seat number of the auditorium			<= 2500	<=1200
Fire resistance class			Class I or II	Class III
Evacuation portion	Door and corridor	Plain, ramp step	0.75	1
	Stairs		0.75	1

5.3.17 The total respective width for evacuation corridor, exit, evacuation staircase and room's evacuation door of the civil buildings, such as schools, shops, office buildings, and waiting rooms for bus, ship or airplane, exhibit hall, places for singing, dancing, amusement and entertainment etc. shall be calculated according to the following requirements:

- The net width of per 100 occupants of the evacuation corridors, exits, stairs and evacuation doors of a room on each floor shall be not less than the requirements of Table 5.3.17-1. If the occupant number on each floor is not the same, the total width of the stairs on each floor may be calculated separately. For the aboveground buildings, the total width of the stairs of the lower floor shall be calculated based on the number of the occupants of the most populous upper floor. And for the underground buildings, the total width of the stairs of the upper floor shall be calculated based on the number of the occupants of the most populous lower floor.

- The total respective width for evacuation corridor, exit, evacuation staircase and room's evacuation door of the public assembly hall or room and places for singing, dancing, amusement and entertainment etc. which are in the basement or semi-basement shall be calculated based on 1m per 100 occupants;

- The total width of the external doors on the first floor shall be calculated depending on the occupants on the floor or the most populous floor above. If the external doors are not used for evacuation purpose for the upper floors, the width may be determined by the occupants of the floor;

- The number of evacuation occupants of video room and cinema shall be calculated based on 1 occupant per square meter according to its building area. And the number of evacuation occupants of other places for singing, dancing, amusement and entertainment etc. shall be calculated based on 0.5 occupant per square meter according to its building area;

- The number of evacuation occupants in shops center be calculated by the building area of business area of each floor multiplying area convert value for aboveground shops should be 50%-70%, and for underground shops, it shall not be less than 70%. The conversion factor of the number of evacuation occupants can be determined according to the requirements in Table 5.3.17-2

Table 5.3.17-1 The net width per 100 occupants of evacuation corridors, exits, stairs and a room's evacuation doors (m)

Stories		Class Type		
		Class I & II	Class III	Class IV
Aboveground	1st &2nd floor	0.65	0.75	1.00
	3rd floor	0.75	1.00	-
	4th & upper floors	1.00	1.25	-
Underground	The distance between the lowest floor and the	0.75	-	-

Table 5.3.17-2 The conversion factor of number of evacuation occupants in shop business area (Person/m2)

Floor	-2F	-1F,1F,2F	3F	4F & upper floors
Conversion factor	0.80	0.85	0.77	0.60

Table 5.3.13 The maximum distance from a room evacuation door that leads directly to the evacuation corridor to the nearest exit (m)

Building			The evacuation door between two exits	The evacuation door located on the two sides of a pecket-shaped corridor or at its extreme end
			Fire resistance class	Fire resistance class
			I & II	I & II
Nursery, kindergarten			25	20
Entertainment area			25	9
Hospital, sanitarium	Single, multiple		33	20
	High-rise	sickroom	24	12
		others	30	15
school	Single, multiple		35	22
	High-rise		30	15
Hotel, residential buildings, Exhibition space			30	15
others	Single, multiple		40	22
	High-rise		40	20

Note:

The direct linear distance from any point in auditorium, exhibition hall, multi-functional hall, dining-room, business area, reading room etc. of Class I or II building to the nearest exit should not be more than 30m. If the evacuation door could not connect with outside space or staircase exit, the corridor should not more than 10m.

For buildings with open external corridors, the maximum distance from the room door to the exit may be increased by 5m based on the requirements in this table;

The safe evacuation distance for building with automatic sprinkler system throughout may be increased by 25% based on the requirements in this table and note 1.

The distance calculation methods of any point in a room to the evacuation door, in a residential building, it shall be from any point in the farthest room to the entrance door of the unit, in an apartment with two stories as one unit, the distance of an inner stair should be calculated by the total length of its horizontal projection.

The staircase on the ground floor should directly to outside, if could not, the staircase on the ground floor should be enclosed staircase or smoke-proof staircase, and the distance between the exit to outside and the staircase should not more than 15m.

The distance from any point in the room to room evacuation door should not more than situation B in the above table.

5.5.21 Except for theater, cinemas, auditorium and stadiums, the minimum net width of escape doors, emergency exits, evacuation corridors and staircase of public building in each floor per 100 occupants should follow the Table 5.5.21-1

Table 5.5.21-1 Evacuation door, Exit, corridor on each floor, D (min)(m/100)

Floor of building		Class
		I、II
Upper ground	1-2 floor	0.65
	3 floor	0.75
	>=4 floor	1
Underground	H<=10m	0.75
	H>=10m	1

H means the distance between ground floor exit height and underground floor height

Table 5.5.18 Minimum width of evacuation door on the ground floor, evacuation corridor and stairs in high-rise buildings per 100 occupants, D (min)(m/100)

High-rise Building	Evacuation door on the ground floor	Evacuation corridor		Staircase
		Single side room	Double side room	
Hospital	1.3	1.4	1.5	1.3
others	1.2	1.3	1.4	1.2

2. Non-propositions

1.0.2 This code shall be applicable to the construction, extension and renovation of the building specified as follows:

- Residential buildings of 9 stories or below (including residential buildings with commercial service facilities)

- Public buildings not over 24m high

- Single story public buildings over 24m

- Underground and semi-underground buildings

- Factory and storage building

5.1.1 Table combustion performance and fire resistance rating of civil building structural members (h)

Structural member		Fire resistance class			
		Class I	Class II	Class III	Class IV
wall	Fire wall	Non-combustible 3.00	Non-combustible 3.00	Non-combustible 3.00	Non-combustible 3.00
	Load-bearing wall	Non-combustible 3.00	Non-combustible 2.50	Non-combustible 2.00	Difficult-combustible 0.50
	Non-load-bearing wall	Non-combustible 1.00	Non-combustible 1.00	Non-combustible 0.50	combustible

	Sidewall of stairway, elevator shaft, wall between units, family separation wall	*Non-combustible 2.00*	*Non-combustible 2.00*	*Non-combustible 1.50*	*Difficult-combustible 0.50*
	Sidewall of exit passageway	*Non-combustible 1.00*	*Non-combustible 1.00*	*Non-combustible 0.50*	*Difficult-combustible 0.25*
	Room partition wall	*Non-combustible 0.75*	*Non-combustible 0.50*	*Difficult-combustible 0.50*	*Difficult-combustible 0.25*
Column		*Non-combustible 3.00*	*Non-combustible 2.50*	*Non-combustible 2.00*	*Difficult-combustible 0.50*
Beam		*Non-combustible 2.00*	*Non-combustible 1.50*	*Non-combustible 0.50*	*Difficult-combustible 0.50*
Floor slab		*Non-combustible 1.50*	*Non-combustible 1.00*	*Non-combustible 0.50*	*combustible*
Roof load-bearing member		*Non-combustible 1.50*	*Non-combustible 1.00*	*combustible*	*combustible*
Evacuation stair		*Non-combustible 1.50*	*Non-combustible 1.00*	*Non-combustible 0.50*	*combustible*
Celling (including ceiling joist 托梁)		*Non-combustible 0.25*	*Difficult-combustible 0.25*	*Difficult-combustible 0.15*	*combustible*

Note: Sidewalls of exit passageway in class I and II civil buildings can be non-combustible with fire resistance rating not less than 0.75h.

The fire resistance rating and combustion performance of structural members of residential buildings may be designed according to the requirements of current national standard Residential Building Code 50368.

3. Ambiguities

5.3.12 The exits and evacuation doors of rooms in basement and semi-basement shall meet the following requirements:

- The exit number of each fire compartment shall be signed according to calculation and not less than two. If two or more fire compartments are on the same floor, each fire compartment may use a fire door in the fire wall which leads to the adjacent fire compartment as a second exit, but each fire compartment must be designed with at least one exit leading directly to the outside;

- If a basement or semi-basement's occupants are no more than 30 and its building area is not more than 500m2, its vertical stairs made of metal leading directly to the outside may be used as the second exit;

- If a room's building are is not more than 50m2 and its occupants are not more than 15, one evacuation door may be provided;

7.1.6 The construction of the fire wall shall be able to keep it standing still even the roof truss, beam or floor slab at its either side is damaged under the effect of fire.

5.3.18 Public assembly building's window and balcony etc. should not be installed with metal barriers. If a metal barrier has to be installed, there shall be a device that can open the barrier from the inside easily. Assistant evacuation facilities should be installed on window and balcony etc.

4. Others

5.3.4 Business hall, Exhibition hall in Class I,II building with Automatic sprinkler system and fire alarm systems decorating with non-burning or difficult burning materials, the S(max) shall:

- setting in high-rise buildings, S<=4000m2;

- setting in single building or the ground floor of multiple building, S<=1000 m2;

- setting in basement or semi-basement, S<=2000m2.

7.1.5 Pipes conveying combustible gas and Class A, B, C liquid are strictly prohibited from penetrating the fire wall. The other pipes should not penetrate the fire wall either, but where there is a pipe penetrating is, fire stopping material shall be used to tightly fill the space between the wall and the pipe, where the pipe is combustible or difficult-combustible, the pipe at both sides of the fire wall shall be fire protected.

5.1.4 The roof slab of Class I and II building shall be constructed with non-combustible materials. The waterproof and thermal insulation layers of the roof can be constructed with combustible materials.

5.1.5 If the floor slab of Class II residential building is pre-stressed reinforced concrete, its fire resistance rating shall not be less than 0.75h.

5.5.7 For high-rise building, a at least one meter width protective overhangs should be set on the top part of building main entrances/exits.

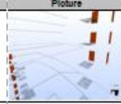
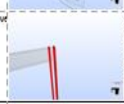
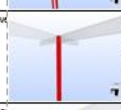
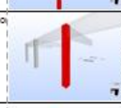
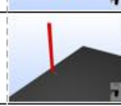
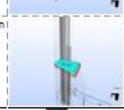
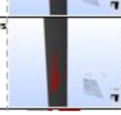
Appendix 3. Issue report of conceptual phase case study

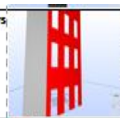
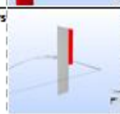
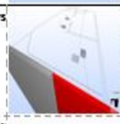
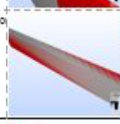
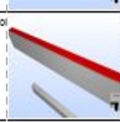
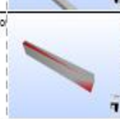
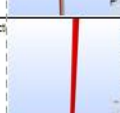
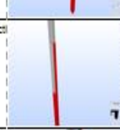
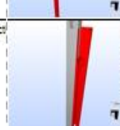
SOLIBRI

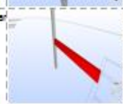
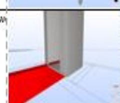
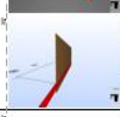
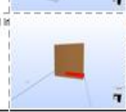
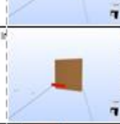
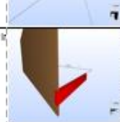
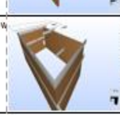
Component Issue Issues (report of conceptual phase case study)

Model Name	01-Architecture-Conceptural Phase SMC Version: 9.5
Checker	yunxue
Organization	
Date	August 14, 2015
01-Architecture-Conceptural Phase	Date: 2015-08-14 12:38:45 Application: Autodesk Revit 2016 (ENU) IFC: IFC2X3

Component Issue

Number	Id	Location	Date	Author	Title	Picture	Issue Description	Issue Comment	Responsibilities	Action Required	Action Taken	Status
1	1	2nd floor, 32nd floor, 13th floor, 16th floor, 1st floor, 28th floor, 23th floor, 3rd floor, 6th floor, 29th floor, 25th floor, 19th	14-Aug-2015	yunxue	Door operation		Doors with type fire protection door don't have information about their operation (e.g. single swing left). Some rules required information about	yunxue, Aug 14, 2015: check original IFC about door operation!!	Yunxue	Modification in original IFC model	to be modified	Open
2	2	3rd floor Area[4]	14-Aug-2015	yunxue	Column Length		Column component(s) have wrong value. The actual value of Property: Length is 116.00 m. ≤ 6.00 m.	yunxue, Aug 14, 2015: Column should be made each level, this rule define the column maximum length in each level, but the original make the column from -3f to top floor, that makes this checking process "NOT	Yunxue	Modification in original IFC model	to be modified	Open
3	3	0-Groundfloor Area[1]	14-Aug-2015	yunxue	conceptural mass		Door Clearance Rule is used to identify the minimum area in frout of door is clear, here found intersection between door and conceptural mass	yunxue, Aug 14, 2015: Delete conceptural mass before export to IFC and import in SMC	Yunxue	Modification in original IFC model	to be modified	Open
4	4	-3rd floor, 1st floor, 0-Groundfloor	14-Aug-2015	yunxue	Unallocated Area		The unallocated area is 82.95 m2. Location: -3rd floor, 1st floor, 0-Groundfoor		Yunxue	Modification in original IFC model	to be modified	Open
5	5	19th floor, 32nd floor, Roof	14-Aug-2015	yunxue	Component above		Column.20.8 doesn't touch components above itself. Distance to the nearest is 800 mm. Location: 19th floor Area[4]		Yunxue	Modification in original IFC model	to be modified	Open
6	6	19th floor, 32nd floor Area[4]	14-Aug-2015	yunxue	Component above		Column.20.9 doesn't touch components above itself. Distance to the nearest is 800 mm. Location: 19th floor Area[4]		Yunxue	Modification in original IFC model	to be modified	Open
7	7	31st floor, 32nd floor	14-Aug-2015	yunxue	Component to co		Similar components that don't touch components above themselves. Distance to the nearest is 800 mm. Location: 31st floor		Yunxue	Modification in original IFC model	to be modified	Open
8	8	6th floor, 5th floor, 7th floor	14-Aug-2015	yunxue	Column 8.2		Column.8.2 doesn't touch components below itself. Location: 7th floor Area[5]		Yunxue	Modification in original IFC model	to be modified	Open
9	9	3rd floor, 2nd floor Area[1]	14-Aug-2015	yunxue	Beam 2.31 issue		Beam.2.31 doesn't touch components above itself. Location: 2nd floor Area[1]	yunxue, Aug 14, 2015: check the origianl IFC, why this beam 2.31 is not connect with slab, is there some design problem?	Yunxue	Modification in original IFC model	to be modified	Open
10	10	32nd floor, Roof Area[4]	14-Aug-2015	yunxue	Beam 33.14 not s		Beam.33.14 doesn't touch components above itself. Location: 32nd floor Area[4]	yunxue, Aug 14, 2015: Check the origianl IFC, why beam 33.14 dont connect to roof?	Yunxue	Modification in original IFC model	to be modified	Open
11	12	2nd floor, 1st floor	14-Aug-2015	yunxue	Auditorium Wall		four auditorium walls are not connect directly to related slab	yunxue, Aug 14, 2015: check the original IFC, why Auditorium Walls are hanging?	Yunxue	Modification in original IFC model	to be modified	Open
12	13	3rd floor, -3rd floor, 12th floor, 13th floor, 0-Groundfoor	14-Aug-2015	yunxue	Space validation		- Components Column.13.10, Column.13.11, Column.13.12, Column.13.7, Column.13.8, Column.13.9, Slab.13.1.1,		Yunxue	Modification in original IFC model	to be modified	Open
13	14	6th floor, -3rd floor Area[4]	14-Aug-2015	yunxue	wall to wall inters		The depth, width, height, and volume of the intersections are: Wall.7.2, Wall.-3.34, 200 mm, 200 mm, 4.00 m, 8.11 m3 Location: 6th floor	yunxue, Aug 14, 2015: check in the original IFC the two wall intersection situation!	Yunxue	Modification in original IFC model	to be modified	Open
14	16	6th floor, -3rd floor Area[4]	14-Aug-2015	yunxue	wall to wall inters		yunxue, Aug 14, 2015: check in the original IFC the two wall intersection situation! Location: 6th floor, -3rd floor Area[4]	yunxue, Aug 14, 2015: Check in the original IFC the wall to wall intersection	Yunxue	Modification in original IFC model	to be modified	Open

15	17	-3rd floor Area[4]	14-Aug-2015	yunxue	wall to wall inters		The depth, width, height, and volume of the intersections are: Wall.-3.29, Wall.-3.5, 300 mm, 150 mm, 69.10 m, 3.11 m3 Location: 6th floor	yunxue, Aug 14, 2015: Check in the original IFC, wall to wall intersection!	Yunxue	Modification in original IFC model	to be modified	Open
16	18	-3rd floor, 0-Groundfoor Area[4]	14-Aug-2015	yunxue	wall to wall inters		The depth, width, height, and volume of the intersections are: Wall.-3.26, Wall.0.13, 2.30 m, 83 mm, 133.00 m, 25.52 m3 Location: 18th floor	yunxue, Aug 14, 2015: check in the original IFC, wall -3.26 is 100% intersected with wall 0.13	Yunxue	Modification in original IFC model	to be modified	Open
17	19	-3rd floor, 0-Groundfoor Area[1]	14-Aug-2015	yunxue	wall to wall inters		The depth, width, height, and volume of the intersections are: Wall.0.16, Wall.-3.1, 200 mm, 150 mm, 14.00 m, 420 l Location: 1st floor	yunxue, Aug 14, 2015: check in the original IFC, wall to wall intersection	Yunxue	Modification in original IFC model	to be modified	Open
18	23	-3rd floor, 0-Groundfoor Area[1]	14-Aug-2015	yunxue	wall to wall inters		The depth, width, height, and volume of the intersections are: Wall.0.6, Wall.-3.7, 200 mm, 150 mm, 13.60 m, 408 l Location: 1st floor	yunxue, Aug 14, 2015: check the original wall to wall intersection	Yunxue	Modification in original IFC model	to be modified	Open
19	25	10th floor Area[2]	14-Aug-2015	yunxue	Beam Intersectio		The depth, width, height, and volume of the intersections are: Beam.11.21, Beam.11.8, 400 mm, 400 mm, 800 mm, 2.65 m3 Location: 6th	yunxue, Aug 14, 2015: Modify the original IFC!	Yunxue	Modification in original IFC model	to be modified	Open
20	26	11th floor, 10th floor Area[2]	14-Aug-2015	yunxue	Beam Intersectio		The depth, width, height, and volume of the intersections are: Beam.12.6, Beam.12.13, 400 mm, 400 mm, 800 mm, 2.65 m3 Location: 6th	yunxue, Aug 14, 2015: modify the original IFC!	Yunxue	Modification in original IFC model	to be modified	Open
21	27	12th floor	14-Aug-2015	yunxue	Beam Intersectio		The depth, width, height, and volume of the intersections are: Beam.13.30, Beam.13.3, 400 mm, 400 mm, 800 mm, 2.65 m3 Location: 6th	yunxue, Aug 14, 2015: modify original IFC1	Yunxue	Modification in original IFC model	to be modified	Open
22	28	7th floor Area[5]	14-Aug-2015	yunxue	Beam Intersectio		The depth, width, height, and volume of the intersections are: Beam.8.21, Beam.8.5, 400 mm, 400 mm, 800 mm, 2.65 m3 Location: 6th floor	yunxue, Aug 14, 2015: modify the original IFC	Yunxue	Modification in original IFC model	to be modified	Open
23	29	8th floor Area[5]	14-Aug-2015	yunxue	Beam Intersectio		The depth, width, height, and volume of the intersections are: Beam.9.47, Beam.9.1, 400 mm, 400 mm, 800 mm, 2.65 m3 Location: 6th	yunxue, Aug 14, 2015: modigy original IFC	Yunxue	Modification in original IFC model	to be modified	Open
24	30	-3rd floor Area[1]	14-Aug-2015	yunxue	Column Intersecti		The depth, width, height, and volume of the intersections are: Column.-3.14, Column.-3.36, 610 mm, 610 mm, 16.10 m, 5.99 m3 Location: 1st floor	yunxue, Aug 14, 2015: modify original IFC	Yunxue	Modification in original IFC model	to be modified	Open
25	31	-3rd floor Area[1]	14-Aug-2015	yunxue	Column Intersecti		The depth, width, height, and volume of the intersections are: Column.-3.17, Column.-3.37, 610 mm, 610 mm, 16.10 m, 5.99 m3 Location: 1st floor	yunxue, Aug 14, 2015: modify original IFC	Yunxue	Modification in original IFC model	to be modified	Open
26	32	-3rd floor Area[1]	14-Aug-2015	yunxue	Column Intersecti		The depth, width, height, and volume of the intersections are: Column.-3.23, Column.-3.41, 610 mm, 610 mm, 16.10 m, 5.99 m3 Location: 1st floor	yunxue, Aug 14, 2015: modify original IFC	Yunxue	Modification in original IFC model	to be modified	Open
27	33	-3rd floor Area[1]	14-Aug-2015	yunxue	Column Intersecti		The depth, width, height, and volume of the intersections are: Column.-3.33, Column.-3.92, 610 mm, 597 mm, 16.10 m, 5.87 m3 Location: 1st floor	yunxue, Aug 14, 2015: modify original IFC!	Yunxue	Modification in original IFC model	to be modified	Open
28	34	2nd floor, -3rd floor Area[1]	14-Aug-2015	yunxue	Column Intersecti		The depth, width, height, and volume of the intersections are: Column.2.12, Column.-3.83, 599 mm, 599 mm, 4.00 m, 1.43 m3 Location: 6th	yunxue, Aug 14, 2015: modify original IFC!	Yunxue	Modification in original IFC model	to be modified	Open
29	35	19th floor, 20th floor Area[3]	14-Aug-2015	yunxue	Column Intersecti		The depth, width, height, and volume of the intersections are: Column.21.11, Column.20.1, 610 mm, 57 mm, 4.00 m, 122 l	yunxue, Aug 14, 2015: modify original IFC	Yunxue	Modification in original IFC model	to be modified	Open

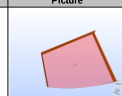
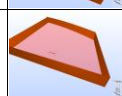
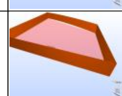
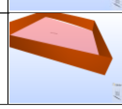
30	36	Area[1]	14-Aug-2015	yunxue	Stair duplicates		stair.1.1 (180mm max riser 275mm tread) and stair.1.4 (180mm max riser 275 mm tread) are duplicates The depth, width, height, and volume of the	yunxue, Aug 14, 2015: check the original IFC stair component	Yunxue	Modification in original IFC model	to be modified	Open
31	37	2nd floor Area[1]	14-Aug-2015	yunxue	stair inside each		Stair 2.3 (180mm max riser 275 mm tread) and stair 2.4 (180 mm max riser 275 mm tread) are inside each other The depth, width, height,	yunxue, Aug 14, 2015: check in the original IFC, if these two stair components are inside each other	Yunxue	Modification in original IFC model	to be modified	Open
32	38	32nd floor, 28th floor Area[4]	14-Aug-2015	yunxue	Column and Bear		The depth, width, height, and volume of the intersections are: Column.29.4, Beam.33.20, 65 mm, 65 mm, 800 mm, 8 l Location: 31st floor	yunxue, Aug 14, 2015: modify the original IFC	Yunxue	Modification in original IFC model	to be modified	Open
33	39	-3rd floor Area[2]	14-Aug-2015	yunxue	Column and Bear		The depth, width, height, and volume of the intersections are: Column.-3.67, Beam.-3.39, 130 mm, 130 mm, 800 mm, 42 l Location: 1st floor	yunxue, Aug 14, 2015: modify the origiani IFC	Yunxue	Modification in original IFC model	to be modified	Open
34	40	7th floor Area[5]	14-Aug-2015	yunxue	Column and Bear		The depth, width, height, and volume of the intersections are: Column.8.2, Beam.8.18, 400 mm, 118 mm, 800 mm, 38 l Location: 6th floor	yunxue, Aug 14, 2015: modify the original IFC	Yunxue	Modification in original IFC model	to be modified	Open
35	41	-3rd floor Area[1]	14-Aug-2015	yunxue	Intersection betw		Beam -3.23 (main beam - 400*800m2) and object - 3.12(Metric CabinFront) are intersection The depth, width, height,	yunxue, Aug 14, 2015: Check in the original IFC the intersection between and Metric CabinFront	Yunxue	Modification in original IFC model	to be modified	Open
36	42	First roof Area[1]	14-Aug-2015	yunxue	roof and beam ins		The depth, width, height, and volume of the intersections are: Beam.4.28, Roof.35.1, 400 mm, 400 mm, 500 mm, 3.40 m3 Location: 1st floor	yunxue, Aug 14, 2015: check the detail drawing, the relationship between roof and beam	Yunxue	Modification in original IFC model	to be modified	Open
37	44	First roof Area[1]	14-Aug-2015	yunxue	roof and beam ins		yunxue, Aug 14, 2015: check the detail drawing, the relationship between roof and beam Location: First roof Area[1]	yunxue, Aug 14, 2015: check the detail drawing, the relationship between roof and beam	Yunxue	Modification in original IFC model	to be modified	Open
38	45	2nd floor Area[1]	14-Aug-2015	yunxue	Beam and Wall Ir		The depth, width, height, and volume of the intersections are: Beam.2.18, Wall.2.3, 31.40 m, 200 mm, 800 mm, 5.02 m3 Location: 6th floor, 1st	yunxue, Aug 14, 2015: this part is Auditorium room, check it in the original IFC	Yunxue	Modification in original IFC model	to be modified	Open
39	46	2nd floor Area[1]	14-Aug-2015	yunxue	Wall and Beam In		The depth, width, height, and volume of the intersections are: Beam.2.46, Wall.2.2, 14.80 m, 200 mm, 800 mm, 2.37 m3 Location: 6th floor, 1st	yunxue, Aug 14, 2015: this part is Auditorium room, check it in the original IFC	Yunxue	Modification in original IFC model	to be modified	Open
40	47	2nd floor Area[1]	14-Aug-2015	yunxue	Beam and Wall In		The depth, width, height, and volume of the intersections are: Beam.2.4, Wall.2.4, 8.61 m, 200 mm, 800 mm, 1.38 m3 Location: 6th floor, 1st	yunxue, Aug 14, 2015: this part is Auditorium room, check it in the original IFC	Yunxue	Modification in original IFC model	to be modified	Open
41	48	2nd floor Area[1]	14-Aug-2015	yunxue	Beam and Wall Ir		The depth, width, height, and volume of the intersections are: Beam.2.6, Wall.2.4, 200 mm, 200 mm, 800 mm, 1.01 m3 Location: 6th	yunxue, Aug 14, 2015: this part is Auditorium room, check it in the original IFC	Yunxue	Modification in original IFC model	to be modified	Open
42	49	2nd floor Area[1]	14-Aug-2015	yunxue	Beam and Wall Ir		The depth, width, height, and volume of the intersections are: Beam.2.4, Wall.2.3, 300 mm, 200 mm, 800 mm, 48 l Location: 6th floor, 1st	yunxue, Aug 14, 2015: this part is Auditorium room, check it in the original IFC	Yunxue	Modification in original IFC model	to be modified	Open
43	50	2nd floor, 3rd floor, 4th floor	14-Aug-2015	yunxue	Auditorium wall w		Auditorium wall wood - 200mm2 and main beam - 400*800 mm all the intersections and issues	yunxue, Aug 14, 2015: check the problems related with Auditorium wall (wood)	Yunxue	Modification in original IFC model	to be modified	Open

Appendix 4. Issue report of legal phase case study (Fire compartment rules)

Fire compartment no Sprinkler

Model Name	Standards layer no mass for fire protection Version: 9.5
Checker	yunxue
Organization	
Date	August 19, 2015
Standards layer no mass for fire	Date: 2015-08-19 00:16:57 Application: Autodesk Revit 2016 (ENU) IFC: IFC2X3

fire compartment

Number	Id	Location	Date	Author	Title	Picture	Issue Description	Issue Comment	Responsibilities	Action Required	Action Taken	Status
1	1	10th floor Area[2]	19-Aug-2015	yunxue	10th floor		Area of the fire compartment is 2,074.80 m2 and the maximum allowed area for the fire compartment with usage type standard area is	the area is too big	Yunxue	Modifiy in original IFC model	to be modified	Open
2	2	11th floor Area[2]	19-Aug-2015	yunxue	11th floor		Area of the fire compartment is 1,975.57 m2 and the maximum allowed area for the fire compartment with usage type standard area is	the area is too big	Yunxue	Modifiy in original IFC model	to be modified	Open
3	3	12th floor Area[2]	19-Aug-2015	yunxue	12th floor		Area of the fire compartment is 1,889.64 m2 and the maximum allowed area for the fire compartment with usage type standard area is	the area is too big	Yunxue	Modifiy in original IFC model	to be modified	Open
4	4	13th floor Area[2]	19-Aug-2015	yunxue	13th floor		Area of the fire compartment is 1,745.91 m2 and the maximum allowed area for the fire compartment with usage type standard area is	the area is too big	Yunxue	Modifiy in original IFC model	to be modified	Open
5	5	14th floor Area[2]	19-Aug-2015	yunxue	14th floor		Area of the fire compartment is 1,672.36 m2 and the maximum allowed area for the fire compartment with usage type standard area is	the area is too big	Yunxue	Modifiy in original IFC model	to be modified	Open
6	8	15th floor Area[2]	19-Aug-2015	yunxue	15th floor		Area of the fire compartment is 1,617.07 m2 and the maximum allowed area for the fire compartment with usage type standard area is	the area is too big	Yunxue	Modifiy in original IFC model	to be modified	Open
7	9	16th floor Area[3]	19-Aug-2015	yunxue	16th floor		Area of the fire compartment is 1,566.00 m2 and the maximum allowed area for the fire compartment with usage type standard area is	the area is too big	Yunxue	Modifiy in original IFC model	to be modified	Open

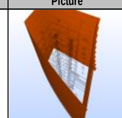
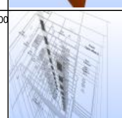
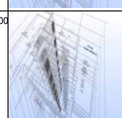
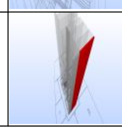
Appendix 5. Issue report of legal phase case study (Room area rules)

SOLIBRI

Related fire protection rule checking issue

Model Name	Standards layer no mass for SMC Version: 9.5
Checker	yunxue
Organization	
Date	August 19, 2015
Standards layer no mass for SMC	Date: 2015-08-19 18:50:20 Application: Autodesk Revit 2016 (ENU) IFC: IFC2X3

related fire protection rule checking issue

Number	Id	Location	Date	Author	Title	Picture	Issue Description	Issue Comment	Responsibilities	Action Required	Action Taken	Status
1	1	18th floor, 19th floor, 14th floor, 16th floor, 11th floor, 10th floor, 17th floor, 15th floor, 13th floor, 12th floor	19-Aug-2015	yunxue	curtain wall		all the curtain wall do not have fire rate!	yunxue, Aug 19, 2015: change in the original IFC to give fire rate!	Yunxue	original IFC modification	to be modified in IFC model	Open
2	2	19th floor, 18th floor, 14th floor, 16th floor, 11th floor, 10th floor, 17th floor, 15th floor, 12th floor, 13th floor	19-Aug-2015	yunxue	fire protection doo		There are fire protection door inDoor components in walls, which aren't fire walls.	yunxue, Aug 19, 2015: change in original wall place to give fire rate	Yunxue	original IFC modification	to be modified in IFC model	Open
3	3	19th floor, 18th floor, 14th floor, 16th floor, 11th floor, 10th floor, 17th floor, 15th floor, 12th floor, 13th floor	19-Aug-2015	yunxue	fire protection doo		There are fire protection door outDoor components in walls, which aren't fire walls.	yunxue, Aug 19, 2015: give fire rate property in IFC	Yunxue	original IFC modification	to be modified in IFC model	Open
4	4	10th floor Area[2]	19-Aug-2015	yunxue	core wall		There are core wall-300SreinforcedconcretWall components in walls, which aren't fire walls. Location: 10th floor Area[2]	yunxue, Aug 19, 2015: give fire rate for core wall	Yunxue	original IFC modification	to be modified in IFC model	Open

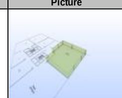
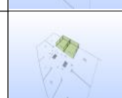
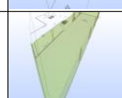
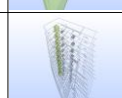
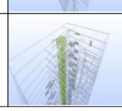
Appendix 6. Issue report of legal phase case study (Others rules)

SOLIBRI

Room area issues

Model Name	Standards layer no mass for SMC Version: 9.5
Checker	yunxue
Organization	
Date	August 20, 2015
Standards layer no mass(room	Date: 2015-08-20 01:24:51 Application: Autodesk Revit 2016 (ENU) IFC: IFC2X3

Room area issues

Number	Id	Location	Date	Author	Title	Picture	Issue Description	Issue Comment	Responsibilities	Action Required	Action Taken	Status
1	19	(B) 10th floor Room[OFFICE 4]	20-Aug-2015	yunxue	office 4		Too large Room spaces. Area of the spaces is 424.19 m2, when the allowed maximum area is 50.00 m2. Location: (B) 10th floor Room[OFFICE 4]	yunxue, Aug 20, 2015: the small office should be less than 50, here should be devided in IFC	YUNXUE	to mdify in original IFC model	change the area of the room	Open
2	20	(B) 12th floor Room[Office 22]	20-Aug-2015	yunxue	small office		Too large Room spaces. Area of the spaces is 97.40 m2, when the allowed maximum area is 50.00 m2. Location: (B) 12th floor Room[Office 22]	yunxue, Aug 20, 2015: this small office should be divided into two in IFC model	YUNXUE	to mdify in original IFC model	change the area of the room	Open
3	21	(B) 12th floor Room[Office 19], Room[Office 18]	20-Aug-2015	yunxue	meeting room		Too large Room spaces. Area of the spaces is 132.40 m2, when the allowed maximum area is 100.00 m2. Location: (B) 12th floor Room[Meeting	yunxue, Aug 20, 2015: change in IFC the meeting room	YUNXUE	to mdify in original IFC model	change the area of the room	Open
4	22	(B) 17th floor Room[Auditorium]	20-Aug-2015	yunxue	Auditorium		Too large Room spaces. Area of the spaces is 430.42 m2, when the allowed maximum area is 400.00 m2. Location: (B) 17th floor	yunxue, Aug 20, 2015: change in the IFC, the max area for auditorium is 400m2	YUNXUE	to mdify in original IFC model	change the area of the room	Open
5	23	(B) 16th floor, (B) 14th floor, (B) 11th floor, (B) 17th floor, (B) 10th floor, (B) 18th floor, (B) 19th floor, (B) 15th floor, (B) 13th floor, (B)	20-Aug-2015	yunxue	WC female		Too small Room spaces. Area of the spaces is 12.79 m2, when the required minimum area is 20.00 m2. Location: (B) 16th floor, (B) 14th floor, (B)	yunxue, Aug 20, 2015: the minimum area for WC is 20m2, should change all the WC in IFC model	YUNXUE	to mdify in original IFC model	change the area of the room	Open
6	24	(B) 16th floor, (B) 14th floor, (B) 11th floor, (B) 17th floor, (B) 10th floor, (B) 18th floor, (B) 19th floor, (B) 15th floor, (B) 13th floor, (B)	20-Aug-2015	yunxue	WC male		Too small Room spaces. Area of the spaces is 12.88 m2, when the required minimum area is 20.00 m2. Location: (B) 16th floor, (B) 14th floor, (B)	yunxue, Aug 20, 2015: the minimum area for WC is 20m2, should change all the WC in IFC model	YUNXUE	to mdify in original IFC model	change the area of the room	Open