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AUTOMATED CHECKING SYSTEM FOR MODULAR BIM OBJECTS

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Abstract. With the increasing popularity of modular buildings, many manufacturers have made BIM objects for use by designers. However, these BIM objects must satisfy specific regulations and requirements, and their quality needs to be verified. In this study, the authors propose an automated checking system for modular BIM object quality verification. The system includes three parts, which are modular BIM object guideline, pre-checking module and automated code checking module. The modular BIM object quality verification system is proposed to be applied to government modular product certification site for checking the modular BIM objects. It is expected that the use of this automated checking system will make it possible to connect users and manufacturers to promote the circulation of modular building products, as well as provide designers with standardized modular BIM objects for design purposes.

Keywords: building information modeling, industry foundation classes, BIM library, modular BIM object, DfMA, sutomated code compliance checking, Building e-submission system.

Introduction

In contrast to other industries, the production efficiency of the construction industry is relatively low. Moreover, most traditional construction methods involve site-based operations with numerous problems, such as poor working environments, frequent occurrence of safety-related accidents, and vulnerability to weather impacts. Therefore, compared with the manufacturing industry, the backward construction process is changing through the design for manufacturing and assembly (DfMA) approach. The modular building method achieves the highest assembly rate in DfMA mode. Consequently, most projects using this method are completed in the factory, making the projects less susceptible to environmental impacts. Meanwhile, production equipment system of the manufacturing industry can be used, which is more difficult to apply in the existing construction process, thereby greatly improving the productivity and reducing the production costs (Lawson et al., 2012; Lee et al., 2015).

Meanwhile, the construction industry is labor-intensive. In places such as Hong Kong and Singapore, the local labor force is relatively small and relies heavily on outside labor. In the era of Covid-19, it is difficult to introduce and manage an external labor force. During this period, it is more advantageous to use combined construction products manufactured in a factory. (Ho, 2016; Legislative Council of the Hongkong Special Administrative Region of the People's Republic of China [LEGCO], 2022; Boxxmodular, 2021).

Therefore, many countries and regions have actively promoted modular construction and adopted corresponding policies, such as the application of prefabricated prefinished volumetric construction (PPVC) in Singapore and the implementation of modular integrated construction (MiC) in Hong Kong. Additionally, practical promotion and on-site use have been conducted (Building and Construction Authority [BCA], 2022a; LEGCO, 2022).

Meanwhile, several governments have also taken measures to review a company's qualifications and certify relevant products, such as the prefabricated bathroom unit (PBU) certification in Singapore (BCA, 2022b), and preaccepted modular integrated construction system certification in Hong Kong (Buildings Department, 2020). However, a BIM model for products certified at these government websites is not required. Only two-dimensional (2D) drawings are available at the Hong Kong MiC site, and the BIM model has not yet been provided.

BIM models have intuitive advantages such as advanced verifiability through various types of communication regarding the methods utilized in the early stages of the design and the ability to simulate the construction

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process. The potential benefits of using BIM to optimize the designs and its application to off-site manufacturing and onsite assembly in DfMA include reduced costs, minimal scheduling, better site safety, less waste, reduced labor, and higher productivity (BCA, 2016).

With the popularization and popularity of modular construction methods, various countries are actively exploring and studying modular-based design methods. For instance, Hong Kong used BIM to create standard modular flats to promote the design efficiency (Hong Kong Housing Authority, 2019). In addition, Cui et al. (2020) proposed selecting and recombining modules in module libraries to obtain a new residential floor plan during the floor design process.

However, the problem is how to obtain modular BIM objects that meet various requirement. Although there are many modular construction companies, they put their BIM objects for designers to choose and use. Various products are available, including modular toilets and modular kitchens, etc. (BIMobject, 2022a; BIMstore, 2022). However, these products differ from general components, they need to satisfy the requirements of certain user functions, building regulations, and corresponding transportation conditions, etc. Even if the designer can download the corresponding modular BIM objects, the quality of each BIM model must be further verified. Owing to the large number of items that need to be confirmed, users are required to spend considerable time and energy checking modular BIM objects. Particularly, for the supply of cross-regional and cross-national modular products, it is necessary to check the BIM model of the suppliers owing to the different regulations in different locations. However, there is a lack of automated verification. Although, users can download a modular library, they cannot directly use the download library.

Recently, several countries have mandated the use of BIM, and with the development of automated code checking technology, it is possible to checking BIM models automatically. Therefore, an increasing number of countries are exploring code-checking technology in the BIM-based building e-submission process.

However, to check some of the building code items, a detailed BIM model must be created. Designers are also required to input a large amount of specific information. This will greatly increase the burden on the designers. For these modular building products, if the manufacturers can provide BIM models that meet building codes, it can greatly facilitate the design and permission processes.

Currently, there are some commercial checking software have also been developed, such as Solibri Checker. However, there is lack of systematic verification system for BIM modular objects. In this study, an automated checking system for modular BIM object quality verification is proposed. It aims at facilitating a quality check for modular BIM objects and provide designers with a source of compliant BIM models.

The remainder of this study is organized as follows: First, the existing research on modular BIM objects and automated code checking is investigated to better understand the latest research trends and breakthroughs. Second, based on the existing research, the authors propose a set of automated checking systems for modular BIM objects and describe the detailed composition of each part. Third, the system was implemented and validated based on a practical case. Fourth, the authors draw out the practical implications of the proposed system. Lastly, the authors summarize and describe the limitations and future research directions.

1. Literature review

In this study, the authors performed a literature review in two parts to develop a modular BIM object verification system based on automated code compliance checking technology. First, the authors consider the aspect of modular BIM objects and then from the aspect of automated code compliance checking.

1.1. Modular BIM object related studies

Since BIM modular objects can be reused to promote the efficiency of a design and the development of modularity, several related studies have been conducted.

Lee and Lim (2012) developed libraries for windows, built-in furniture, kitchen systems, and removable bathrooms based on a single-room prototype of urban living houses. When an engineer inserts the working tolerance into the BIM library, the fabricating reference plane is generated automatically, and several categories related to work reference are supplemented. This study primarily focused on exploring the development process of family libraries.

Koh et al. (2016) conducted basic research on a modular-based BIM library customized for housing for the elderly. Accordingly, the authors analyzed the behaviors of the elderly and the residential design technique, modular housing, BIM library, and the standards relevant to housing for the elderly in Korea, the study entailed the development of customized guidelines and BIM libraries for the entrance, kitchen, and bathroom.

Cui et al. (2020) proposed the selection and recombination of modules in module libraries to obtain a new residential floor plan during the floor-design process. When the types of modules in module libraries are sufficiently rich, the modules that satisfy the requirements can be selected quickly and combined based on the owner's needs to significantly enhance the design efficiency. The authors highlighted the lack of rich modular libraries as the fundamental problem.

1.2. Previous research on automated code compliance checking

Recently, automated code compliance checking has been studied for applications in various domains, such as building envelope design, building water network design, and evacuation design (Tan et al., 2010; Martins & Monteiro, 2013; Choi et al., 2014). However, code checking is based on BIM data. The quality of BIM data should be guaranteed to ensure the accuracy of the results. The authors

divided the investigation of automated code compliance checking into two parts, one part is automated code checking, another part is BIM data quality checking for ensuring the accuracy of the checking results.

1.2.1. Automated code checking related studies

Eastman et al. (2009) analyzed the rule-checking efforts of CORENET in Singapore, Statsbygg in Norway, Design Check in Australia, International Code Council, and GSA Design Check in the USA and mentioned four types of functions that rule-based checking systems should support: rule interpretation, building model preparation, rule execution, and rule reporting, as well as other required internal functions.

Choi et al. (2014) developed an automated evacuation prototypical checking system called InSightBIM evacuation that allow designers and owners to check BIM data for compliance with evacuation rules.

Getuli et al. (2017) applied an automated code-checking method in site safety planning to support decision making. The study aimed to define the design and verification workflow for the "Health and safety" BIM-based design and specify the minimum requirements and mandatory information content for submission of construction site layouts and safety plans.

Sun et al. (2019) proposed the development of rule-based automated design checking for modular buildings harnessing the concept of design for manufacturing, transportation, and assembly (DfMTA).

1.2.2. BIM data quality checking related studies

Eastman et al. (2009) proposed that a syntax check should be performed before conducting code checking, the syntax check aims to check whether the building model contains the properties, names, and objects required to complete the checking task.

Shin et al. (2015) established an automated BIM quality pre-checking system to enhance BIM design quality effectively and efficiently. The pre-checking items had two parts: general items and code-checking related items.

Kim et al. (2019) proposed a pre-checking module for use in the KBIM e-submission process in which BIM data should be checked before submitting the IFC files to the e-submission system.

1.3. Summary

Through investigation and research, scholars have recognized the significance of the diversity of modular BIM objects in promoting the design of modular buildings using BIM. Meanwhile, considering the diversity of human needs, it is necessary to analyze such different needs and formulate relevant BIM guidelines for specific purposes.

Existing automated checking technologies have been applied in many fields to check BIM models. However, the quality of the BIM is imperative to guarantee automated code-checking results. Prior to implementing automated code checking, it is crucial to check the quality of the BIM.

Furthermore, it is imperative to provide a complete set of automated checking systems for modular BIM objects to provide a variety of BIM objects that satisfy the requirements of modular design. In the next section, we propose a quality verification method for modular BIM objects based on automated code compliance checking technology.

2. Methodology for developing automated checking system for modular BIM objects

Based on previous studies, the authors propose the following automated verification system to provide a series of verification for modular BIM objects (Figure 1).

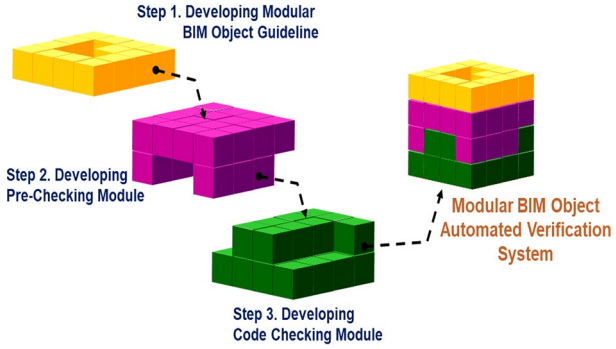

Figure 1. Process of developing modular BIM objects automated verification system (Sun & Kim, 2020)

Step 1: Based on the different purposes of the modular BIM object, various requirements are analyzed to develop the related modular BIM object guideline.

Step 2: A pre-checking module is developed to pre-check the quality of the modular BIM object.

Step 3: Based on the developed modular BIM object guideline, an automated code compliance checking module is developed for the checking items.

The detailed development of each part is described in the following sections.

2.1. Development of modular BIM object guideline

Based on the specific type of modular products (such as bathrooms for the disabled, kitchens for the elderly, and children's bedrooms), the developer of the modular BIM object guideline should analyze the requirements of specific purpose, the modular product related requirements and the building code rated requirements, to sort out related modular product guidelines, including the information about product size, material, traffic restrictions of related areas, connection, and waterproofing, etc. (Figure 2). Additionally, relevant ISO standards should also be considered in the formulation of dimensions, such as series of preferred multimodal sizes for horizontal dimensions mentioned in ISO 6513:1982 (International Organization for Standardization [ISO], 1982).

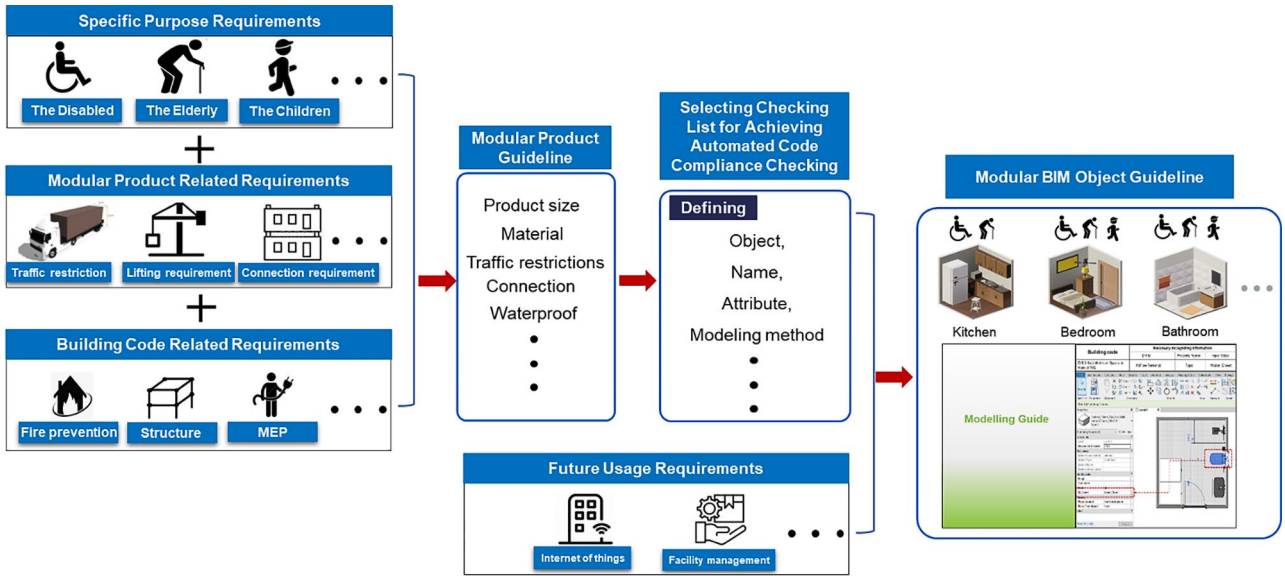

Figure 2. Process of modular BIM object guideline development

The next step involves selecting the items that can be achieved using the BIM model and checked using automated code checking technology. Considering the convenience of user modeling, a national name classification and unity of information exchange between various administrative departments of building approval should be defined, including the object, name, attribute, and modeling method.

In the process of creating the guideline, the related administrative departments of building approval should be invited to participate to provide the necessary information (such as the name classification), facilitate coordination and make decisions by consulting the industry when the modeling methods or the required input information needs to be confirmed. Meanwhile, basic modeling examples should be provided to help users better understand the guideline.

In addition, the developer of the modeling guideline could specify other additional attributes or names, such as information related to the Internet of Things (IoT) or Facility Management (FM), based on the requirements of future usages.

2.2. Development of pre-checking module

A pre-checking module was developed to check whether it has the fundamental conditions for achieving automated code compliance checking (see Figure 3). It is necessary to confirm the input information in advance and check the quality of the BIM model, in order to ensure the results of the automated code checking. For example, some checking items require the creation of a "space" object to perform automated code checking, whereas some checking items require inputting specific names or attributes. If the system cannot detect this information, the results of the check will be inaccurate (Korea Agency for Infrastructure Technology Advancement [KAIA], 2017).

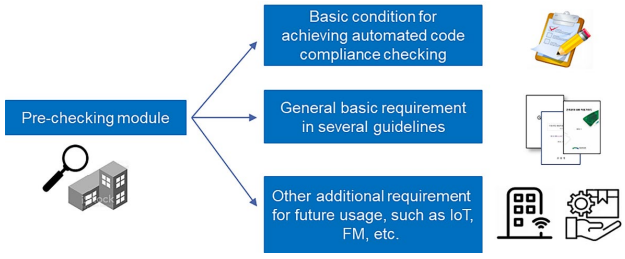

Figure 3. Pre-checking module for modular BIM object

Meanwhile, the pre-checking module should also have other functions for checking the general fundamental requirements specified in several national BIM guidelines, such as whether an external wall property is provided, or language input is correct.

In addition, according to the developed modular BIM object guideline, if there is an additional requirement for attributes or names related to the IoT and FM, the related information should also be pre-checked (KAIA, 2017).

2.3. Development of automated code checking module

The automated code checking module should be developed for items that are selected using the BIM model and checked using automated code checking technology. Because different authoring tools produce different kinds of native files formats (Harty et al., 2015), it is difficult to perform checking according to each format. Since Industry foundation classes (IFC) is an open international standard for the BIM data and registered as ISO 16739-1:2018 by ISO (2018), it has also been widely supported by most BIM software companies (BuildingSmart International [BSI], 2022a). Therefore, IFC data model is selected as the target format for automated code checking (Kim et al., 2020a).

The automated code checking module should comprise an IFC viewer function, code checking function, and reporting function, as shown in Figure 4.

The IFC viewer function helps visualize the IFC data model for users and provides the necessary information for various logic operations.

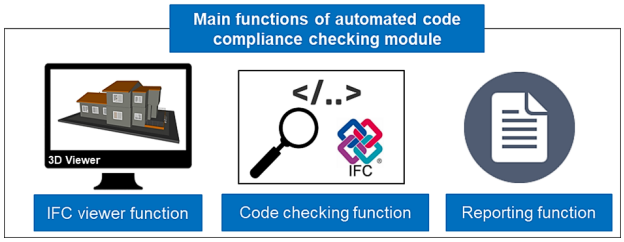

Figure 4. Main functions of the automated code compliance checking module

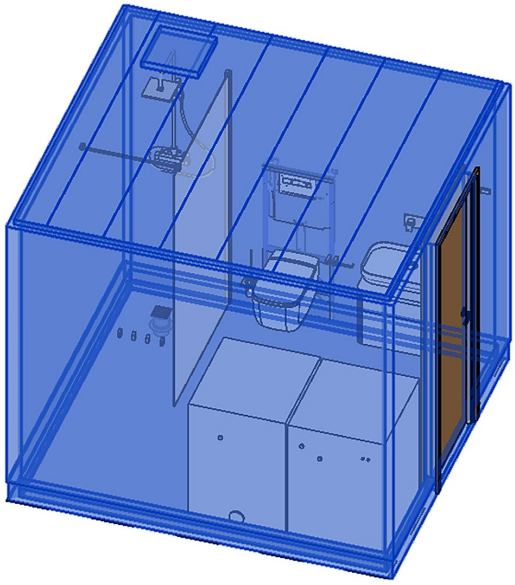

Figure 5. Prefabricated bathroom BIM object (BIMobject, 2022b)

The code-checking function checks whether the IFC data model conforms to the predefined logic code.

The reporting function is used to export the results of the automated code compliance checking (KAIA, 2017).

3. Case study

The authors selected a Singapore accessible bathroom-related building code for the implementation of the system to verify the concept. Accordingly, the authors downloaded the actual model from a BIM object website (BIMobject, 2022b) and modified the model to demonstrate the verification (Figure 5). Therefore, this study has practical significance.

3.1. Modular BIM object guideline

The authors analyzed the accessible bathroom-related building codes and related standards to establish the modular BIM object guideline (Figure 6).

Figure 7 illustrates an example of specifying "Water_Closet" in Revit, which should be specified in the modular BIM object guideline to help users understand it.

3.2. System implementation

The automated code-checking function is a vital aspect, and the authors will provide more information about the development of the code-checking function. Rule-based quality checking software Solibri Office was selected as the target software to demonstrate the development of programming details for automated code checking function.

The authors will consider the example of checking the "door width", which is required to be more than 850 mm. The authors will demonstrate the development process by coding a separate rule set (Figure 8), without using the basic rule set provided internally by the Solibri, the ruleset was implemented by utilizing the Java API provided by Solibri (2020).

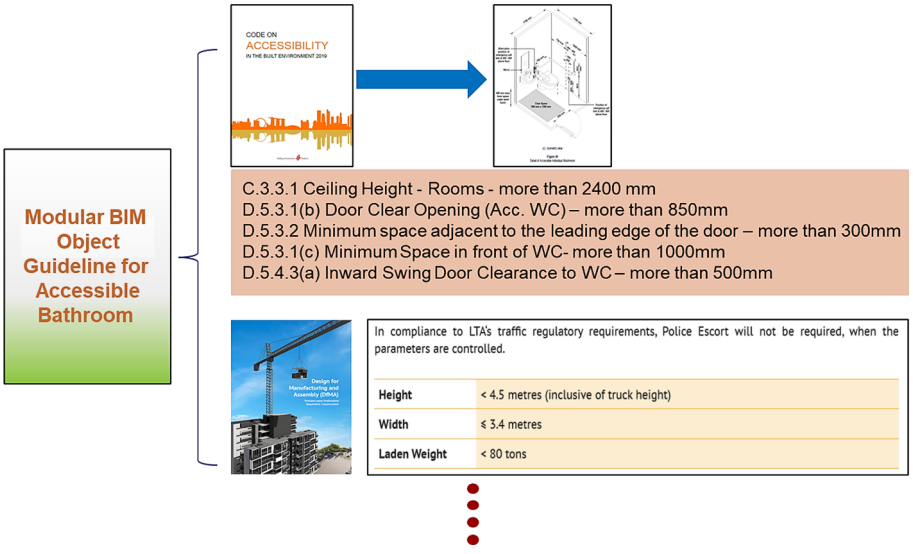

Figure 6. Modular BIM object guideline for accessible bathroom

The modular BIM object model was checked after loading developed code checking rule into Solibri office. The results of the door-width checking are shown in Figure 9.

The authors participated in the Singapore 2-Stage Innovation Grant project "automated code compliance check in BIM" and employed the SBim Assess (Kim et al., 2020b) that was developed in the project to demonstrate the code checking module to check item "D.5.3.1(c)' Minimum Space in front of WC", as shown in Figure 10.

3.3. Discussion of the case study

In the case study, the authors chose a Singapore accessible bathroom-related building code to implement the system to verify the proposed method. From current technology, it is possible to create modular BIM object guideline and develop a corresponding modular BIM object verification system. Moreover, the quality of modular BIM objects can be checked through the verification of the system. If designers use the verified modular BIM object for design, there will be fewer manual checks of many specification provisions to improve design productivity.

Since the automated code checking system relies on the identification of names, attributes and BIM objects (Eastman et al., 2009), there are also very detailed checking items for such modular products, which requires designers to make detailed BIM models, such as creating "water closet" BIM object together with a specified name. It could be a great burden for designers to create such an accurate model that can satisfy the requirements of an automated verification system. Generally, BIM models created by designers are different from the actual product, and there is no guarantee that the BIM model will be

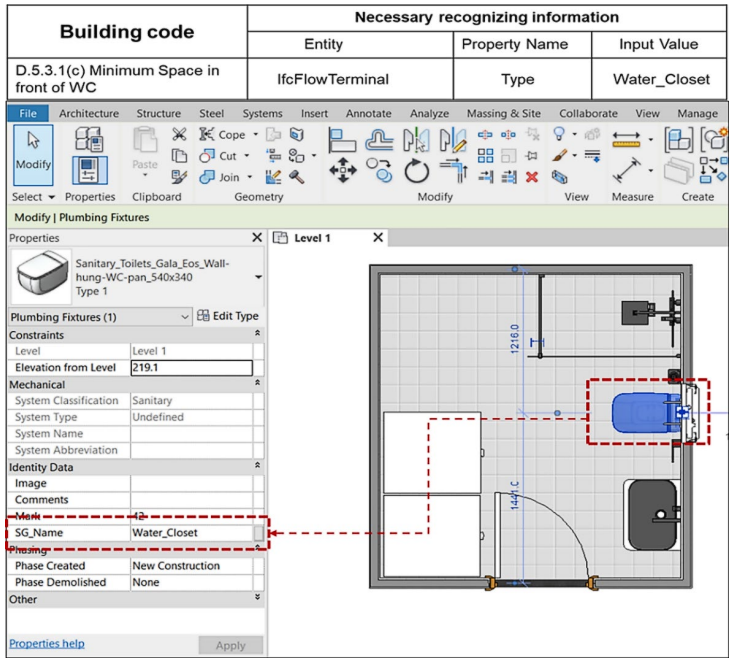

Figure 7. Example of specifying "Water_Closet" under SG_Name

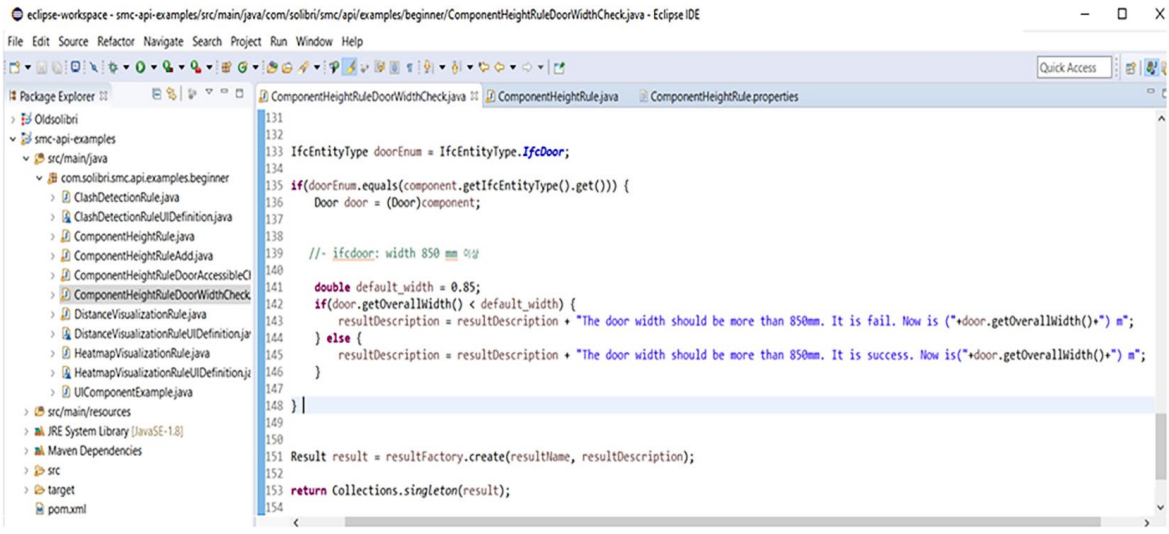

Figure 8. Example for developing the code checking rule for checking the door width (Eclipse)

followed in the construction process in the future; these modular products need to be purchased in practice. If the BIM model can be provided by a modular manufacturer and used in the design process, it will significantly reduce the modeling burden of designers.

If manufacturers are required to develop BIM models for their modular products, a modular product is typically produced in batches, and numerous products will share the same BIM object model. In general, the burden of modeling was not outstanding. If designers use their BIM models for design, it is also a type of publicity for their modular products. Meanwhile, they also occupy a large competitive advantage in the stage of purchasing products in the construction process. Therefore, the authors propose developing a modular BIM object verification system to allow modular manufacturers to provide qualified modular BIM objects for use by designers.

Meanwhile, since the modular BIM object verification system includes the checking of relevant building regulations, the process of building approval will be greatly increased if the system shares a set of unified checking rules with the government BIM-based building approval system, and designers use these verified BIM objects for design.

4. Practical implications

Following the development of such a modular BIM object verification system, its application to government or relevant institutions modular product certification sites is proposed (Figure 11). Furthermore, manufacturers should be required to provide the related modular BIM objects through the verification system when obtaining certification for modular products.

The supply of transnational products has become increasingly common, with the recent prosperity and development of market commodities and the diversification of demand, along with the development of networks and logistics. Accordingly, the circulation of cross-regional construction products has become extremely frequent. Currently, web services such as "BIMobject" and "BIMstore" provide production products and related BIM objects, providing convenience for manufacturers to provide products and for designers to use BIM objects for design.

However, building products, particularly modular building products, must satisfy local building regulations if they venture into another country or region. Even though, the range of checking building regulations is similar in different countries and regions. However, the de-

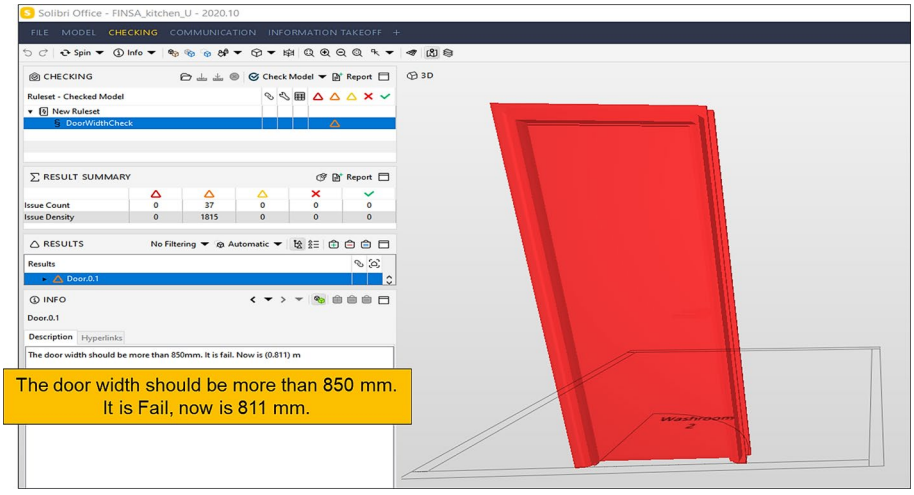

Figure 9. Result of "Door Width Check"

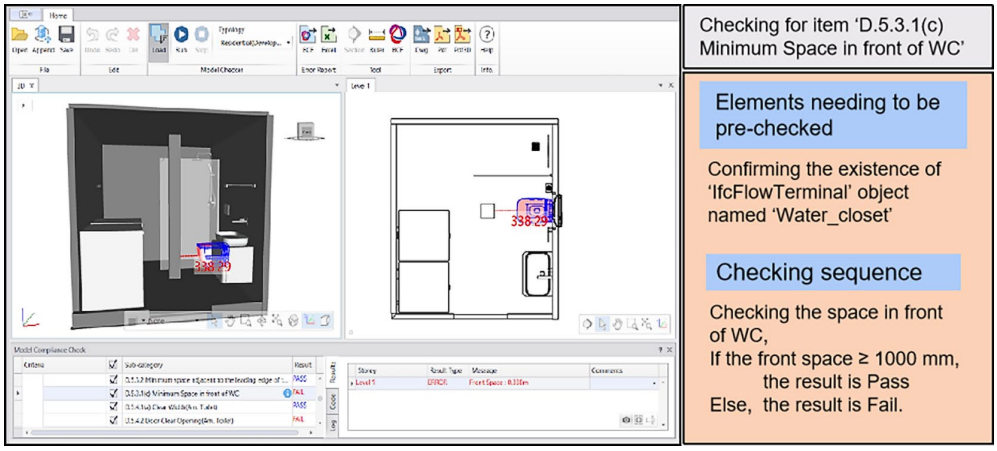

Figure 10. Example of checking item "D.5.3.1(c) Minimum Space in front of WC"

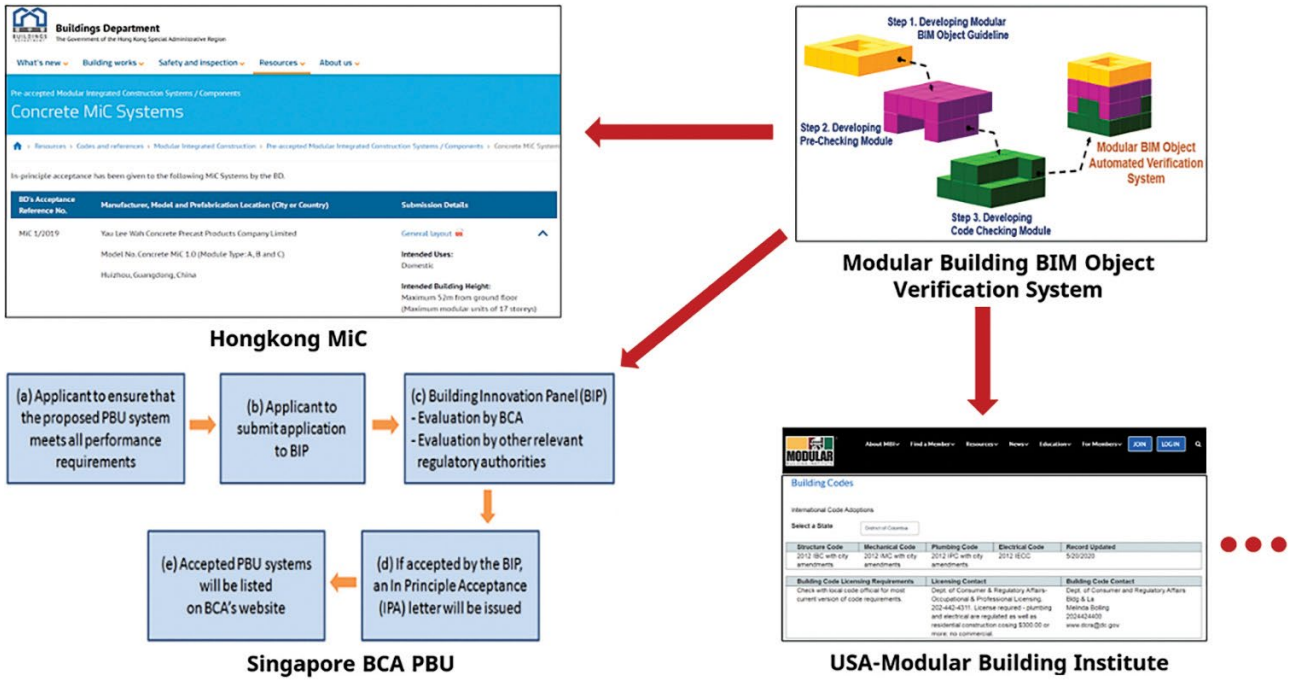

Figure 11. Application of the modular building BIM object verification system to modular product certification site

tailed items and specific dimensions of such checks will be more or less different. For example, the authors conducted a brief survey of some checking items for accessible toilets in Singapore, South Korea, and China (BCA, 2019; Ministry of Government Logislation South Korea [MGLSK], 2018; Ministry of Housing and Urban-Rural Development of the People's Republic of China [MOHURD], 2012), as shown in Table 1.

Therefore, it is critical for cross-regional suppliers to obtain the required information for the supplied areas. The verification of modular products requires the participation of the government building approval authority. The design based on BIM will be also used in the BIM-based building administrative approval process which is directly related to the government building approval authority.

Within the buildingSMART International (BSI), a "Regulatory Room" was established, which is led by a steering committee comprising representatives from international members and local buildingSMART chapters. The purpose of the Regulatory Room is to enable project owners and regulatory authorities to benefit from the use of openBIM (BSI, 2022b).

Since the Regulatory Room is leading the development of international automated compliance checking technology. The modular BIM object verification system is also based on automated compliance checking technology. Therefore, the authors also propose promoting modular BIM object verification system through the "Regulatory Room".

Furthermore, a management platform for modular building products based on a modular BIM object verification system is to be established under the leadership of BSI. Accordingly, each building SMART chapter develops its distinct regional modular BIM object verification system and provides relevant modular BIM object guidelines (Table 2). Worldwide modular building suppliers are invited to create BIM models of corresponding modular products according to the modular BIM object guideline. The verified modular BIM objects will become the timely updated standard BIM library of modular products of the corresponding country. Consequently, it can facilitate the use of designers, in addition to promoting the products of the suppliers.

Other related services, such as modular product company certification, logistics certification, and material certification, can be expanded by using the credibility and influence of the BSI, with a focus on this modular building products management platform. Accordingly, the international modular building market will be guided in a standard

Table 1. Some checking items for accessible toilets in Singapore, South Korea, and China

Checking item \ Country	Singapore	South Korea	China
Door clear width	850 mm	900 mm	800 mm
Toilet seat height	450–480 mm	400–450 mm	450 mm
. . .			

Table 2. Modular BIM object modeling guides for different products in different countries or regions

		Modular BIM object type			
		Kitchen	**Bathroom**	**Lift**	…
Target country/ Region	**Singapore**	Modeling guide	Modeling guide	Modeling guide	
	Hong Kong	Modeling guide	Modeling guide	Modeling guide	
	Korea	Modeling guide	Modeling guide	Modeling guide	
	. . .				

and orderly manner. The standard BIM data of modular products obtained through this platform will also become a primary source of building data in various countries.

Conclusions

In this study, a quality verification method for modular BIM objects based on automated code compliance checking is proposed. This can become a platform that connects designers and suppliers when applied to the modular building product certification site of a government or relevant institution.

As there are different regional regulations, the proposed method will play a crucial role in providing information on the modular requirements for other areas for cross-regional modular supply.

The verified BIM modular object can serve as a national real-time update standard BIM library. Designers can use standard modular BIM objects to improve the design productivity. As modular BIM objects are directly connected to modular products in reality, modular products can be purchased directly after the design is completed. Through this method, the design changes can be reduced, and it is also a feasible way to realize integrated project delivery (IPD).

Because the modular BIM object verification system uses the same ruleset as the national BIM-based building e-submission system, if the designers use the verified modular BIM object for designing, it can facilitate the building e-submission process.

However, to verify the concept, authors only chose a Singapore accessible toilet-related accessible building code for the implementation of the system. In fact, many items need be verified for modular products. Some of these can be expressed using BIM, such as dimension compliance verification. However, some items require checking using other methods, such as waterproof testing. Prior to establishing the modular BIM object verification system, it is necessary for the certification department to sort out the suitable items for automated code checking.

The government or relevant institutions should be mobilized to promote the development of a modular building product BIM object verification system. Supplies are required to submit BIM models of relevant products and obtain verification through the system when they supply modular building products. Subsequently, the related transportation service, company credit evaluation service, operation and maintenance management service, recycling service, and other related services can be expanded as needed by considering the modular building BIM object verification system as the center.

Currently, big data and artificial intelligence technologies are being used in the Architecture, Engineering and Construction (AEC) Industry. However, related studies in this area are limited owing to inadequate data in the AEC industry. Verified modular BIM objects are expected to provide important standard BIM data resources. Moreover, it will become an important database for smart cities with the increase in standardized data, such as IoT and FM related data attached to modular buildings.

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Author contributions

H.W. Sun was responsible for the paper conceptualization, paper methodology and paper writing, I.H. Kim was responsible for the project administration, paper methodology, funding acquisition, research guidance, paper review.

Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work described in this paper.

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