

**A BIM BASED APPROACH FOR AUTOMATED
COMPLIANCE CHECKING OF RESIDENTIAL BUILDING
DESIGNS WITH BUILDING CODE IN SAUDI ARABIA**

BY

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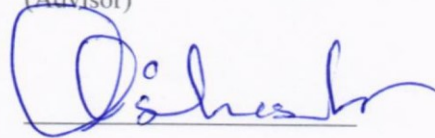
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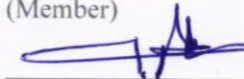
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Dedication

I dedicate this thesis to those who have inspired, supported, and guided me on this journey of learning and discovery.

I am deeply grateful to my mom (**Umm Zayed**), brothers (**Zayed, Nader**), and sisters (**Umm Luay, Umm Ali, Umm Hussan ,Umm Bisan, Umm Yaqeen**) whose unwavering love, patience, and encouragement laid the foundation for my growth. Your belief in me has been my greatest motivation. I would also like to thank all my previous teachers, as their hard work laid the foundation for this work. I am also grateful to my friends and colleagues for their support and comforting words during difficult times.

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LIST OF ABBREVIATIONS

ACC	:	Automated Compliance Checking
AEC	:	Architecture, Engineering, and Construction
BIM	:	Building Information Modeling
BIM SBC Tool:		Building Information Modeling for Saudi Building Code Tool
CAD	:	Computer- Aided Design
DSR	:	Design Science Research
IFC	:	Industry Foundation Classes
MOMRA	:	Ministry of Municipalities and Rural Affairs
NLP	:	Natural Language Processing
RASE	:	Requirement, Application, Selection, and Exceptions
SBC	:	Saudi Building Code
VPL	:	Visual Programming Language

]

ABSTRACT

Full Name : [Bandar Sultan Abdo Esmail Al-Absi]
Thesis Title : **[A BIM BASED APPROACH FOR AUTOMATED COMPLIANCE CHECKING OF RESIDENTIAL BUILDING DESIGNS WITH BUILDING CODE IN SAUDI ARABIA]**
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[In January 2024, Saudi Arabia launched a digital transformation initiative in the construction sector, mandating the use of Building Information Modeling (BIM) for architectural plans in all building projects. The Ministry of Municipal and Housing requires engineering offices to submit 3D design models, enabling data storage, enhanced error detection, and improved compliance verification. This research proposes an automated framework for checking residential building designs against the architectural requirements of the Saudi Building Code, using BIM models developed in Autodesk Revit 2024 and integrated with Dynamo 2.1. The framework introduces a five-step methodology—specification checking, digital environment implementation, requirement deciphering, calculation, and compliance result analysis providing a real-time decision-support tool for designers and a fast compliance-checking system for municipalities. By digitizing complex regulatory rules and integrating them into BIM workflows, the study streamlines compliance verification, reduces errors, and enhances process efficiency. The scalable framework adapts to varying building codes and mandatory requirements, supports design variations, and addresses challenges like high maintenance costs and limited flexibility in existing methods. Additionally, it aligns sustainability goals by minimizing resource waste and opens opportunities for integrating emerging technologies, such as artificial intelligence (AI), to further revolutionize construction regulation and foster global collaboration.]

ملخص الرسالة

الاسم الكامل: بندر سلطان عبده إسماعيل العبسي

عنوان الرسالة: نهج قائم على نموذج معلومات البناء للتحقق الآلي من امتثال تصميمات المباني السكنية مع قانون البناء في المملكة العربية السعودية

التخصص: هندسة معمارية

تاريخ الدرجة العلمية: ديسمبر 2024

في يناير 2024، أطلقت المملكة العربية السعودية مبادرة للتحويل الرقمي في قطاع البناء والتشييد، حيث فرضت استخدام نمذجة معلومات البناء (BIM) للمخططات المعمارية في جميع مشاريع البناء. تشترط وزارة البلدية والإسكان على المكاتب الهندسية تقديم نماذج تصميم ثلاثية الأبعاد، مما يتيح تخزين البيانات وتعزيز اكتشاف الأخطاء وتحسين التحقق من الامتثال. يقترح هذا البحث إطار عمل آلي للتحقق من تصاميم المباني السكنية مقابل المتطلبات المعمارية لكود البناء السعودي، باستخدام نماذج نمذجة معلومات المباني المطورة في نظام أوتوديسك ريفيت 2024 والمدمجة مع دينامو 2.1. يقدم إطار العمل منهجية من خمس خطوات - التحقق من المواصفات، وتنفيذ البيئة الرقمية، وفك رموز المتطلبات، والحساب، وتحليل نتائج الامتثال مما يوفر أداة دعم اتخاذ القرار في الوقت الفعلي للمصممين ونظامًا سريعًا للتحقق من الامتثال للبلديات. من خلال رقمته القواعد التنظيمية المعقدة ودمجها في تدفقات عمل نمذجة معلومات البناء، تعمل الدراسة على تبسيط عملية التحقق من الامتثال وتقليل الأخطاء وتعزيز كفاءة العملية. يتكيف إطار العمل القابل للتطوير مع قوانين البناء المتنوعة والمتطلبات الإلزامية، ويدعم اختلافات التصميم، ويعالج تحديات مثل ارتفاع تكاليف الصيانة والمرونة المحدودة في الأساليب الحالية. بالإضافة إلى ذلك، فهو يعمل على موازنة أهداف الاستدامة من خلال تقليل هدر الموارد إلى أدنى حد ممكن، ويفتح فرصًا لدمج التقنيات الناشئة، مثل الذكاء الاصطناعي، لزيادة ثورة في تنظيم البناء وتعزيز التعاون العالمي.

CHAPTER 1

INTRODUCTION

1.1 Background

The Saudi construction industry has rapidly grown over the past decade, resulting in experts coming to Saudi Arabia from all over the world [1] . In their annual report, Gulf Business predicted a value of \$120.4 billion in building projects in 2021 and an average annual growth rate of 4% or higher from 2023 to 2026 [2]. Several challenges and opportunities exist in the construction industry in Saudi Arabia. One challenge is the lack of adequate experience of engineers and project managers in building information modeling (BIM) [3] which has become one of the essential skills for construction professionals in recent years. Another challenge is the poor safety performance on construction sites, which necessitates the establishment of a national governance structure to improve safety practices and overcome barriers [4]. The construction industry in Saudi Arabia is moving towards regulations and standards that are performance-based when it comes to technology.

Construction, design, safety, and overall building welfare are all controlled by sets of rules and regulations known as building codes and regulations [[5], [6]]. A building code is a legal document issued by local, state, or national governmental authorities to establish minimum acceptable standards for construction practices [7]. According to the Saudi

Building Code (SBC), it is defined as the set of laws and requirements pertaining to building and construction to guarantee safety and public health [8]. On the other hand, building standards are technical documents that establish uniform criteria for several aspects of building construction, such as quality, performance, size, or procedure [[7], [9]].

Building codes ensuring safety, health, and sustainable construction practices, as well as consistent standards in construction [10]. They provide guidelines and requirements for various aspects of building construction, design, and maintenance [11]. With time, building codes and regulations have undergone change, become more sophisticated, and are being enriched with the infusion of new knowledge into the construction and design domains [12].

Numerous studies have been conducted on building codes and regulations in Saudi Arabia. These building codes are official legal documents that people are free to interpret and apply. They are hardly as precise as formal logic. But the engineers, architects, and contractors should be able to read those documents and transform them into scientific notations and software applications [13]. The technical aspects and required standards of a building are defined by an extensive set of rules and regulations in the Architecture, Engineering, and Construction (AEC) industry.

Building codes can be broadly categorized into those that apply to the entire building, such as the International Building Code (IBC) [14] and the International Fire Code (IFC) [15], and those that apply to specific parts or components of a building, such as the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard

90.1 and the International Energy Conservation Code (IECC). Compliance with building codes is crucial for disaster resilience and the prevention of building failures.

The process of conventional methods of code compliance checking is laborious and costly. For example, issuing building permits in Chicago takes a mean time of 72 days at a minimum fee of 301 USD [[17], [18]]. Automated compliance checking (ACC) effectively reduces the challenges associated with manual code compliance reviews by lessening the workload of design reviewers. ACC utilizes software tools and algorithms to automatically compare building plans with relevant building codes. [18]. Compared to the conventional method, ACC is anticipated to save time, effort, and money while simplifying the work of design reviewers [19].

The potential advantages of ACC encompass expediting the implementation of BIM in the AEC sector [20], fostering the implementation of a standardized format for the exchange of information in the AEC industry [21], and stimulating the utilization of computational techniques and logical reasoning in the AEC field [22]. Code compliance checking has recently been integrated into various systems by government agencies and local jurisdictions worldwide. Many of these systems have concentrated on ensuring adherence to building codes. The scope and original jurisdictions of ACC are summarized in Table 1 [23]. ACC has been a prominent research subject worldwide for over 50 years. Some systems have advanced to a higher level of maturity due to the progress in applications and computing technology driven by the industry's focus on productivity and innovation enhancement elements. Figure 1 illustrates the key milestones and developments in the history of ACC systems.

Considering the numerous advantages, the investigation of ACC originated in the 1960s which is the first successful effort for code compliance checking, when Fenves devised a decision table system to verify that the design of steel structures is in accordance with the specifications of the American Institute of Steel Construction (AISC) [24]. Fenves and Garrett suggested utilizing information networks to depict design standards in the ACC systems [25]. Expert ACC systems like SICAD [26], SPEX [27], and the Design Prototype system emerged during the same time as expert systems.

Table 1 The current situation with ACCC in different countries.

System	Building code	Energy code	Fire code	Initially created
SMARTcodes	Partial	-	-	International
COMcheck=REScheck	Partial	X	-	United States
DesignCheck	Partial	-	-	Australia
EDModelChecker	Partial	-	-	Norway
Solibri Model Checker	Partial	-	Partial	Finland
FORNAX	Partial	-	x	Singapore

Researchers demonstrate significant optimism in utilizing BIM. It is expected that BIM will be able to seamlessly operate across various platforms for designers, contractors, clients, vendors, and other stakeholders [28]. Building information modeling is a worldwide digital technology that is transforming the construction sector and is considered to have the capacity for significant advancements [29]. The implementation of BIM as a digital representation of buildings resulted in the development of BIM-based ACC systems. Solibri Model Checker (SMC) initially functioned as a BIM validation tool, but it quickly developed into a tool that automates the process of checking code compliance [30]. A lot

of researchers have investigated how BIM and automated code compliance checking might work together.

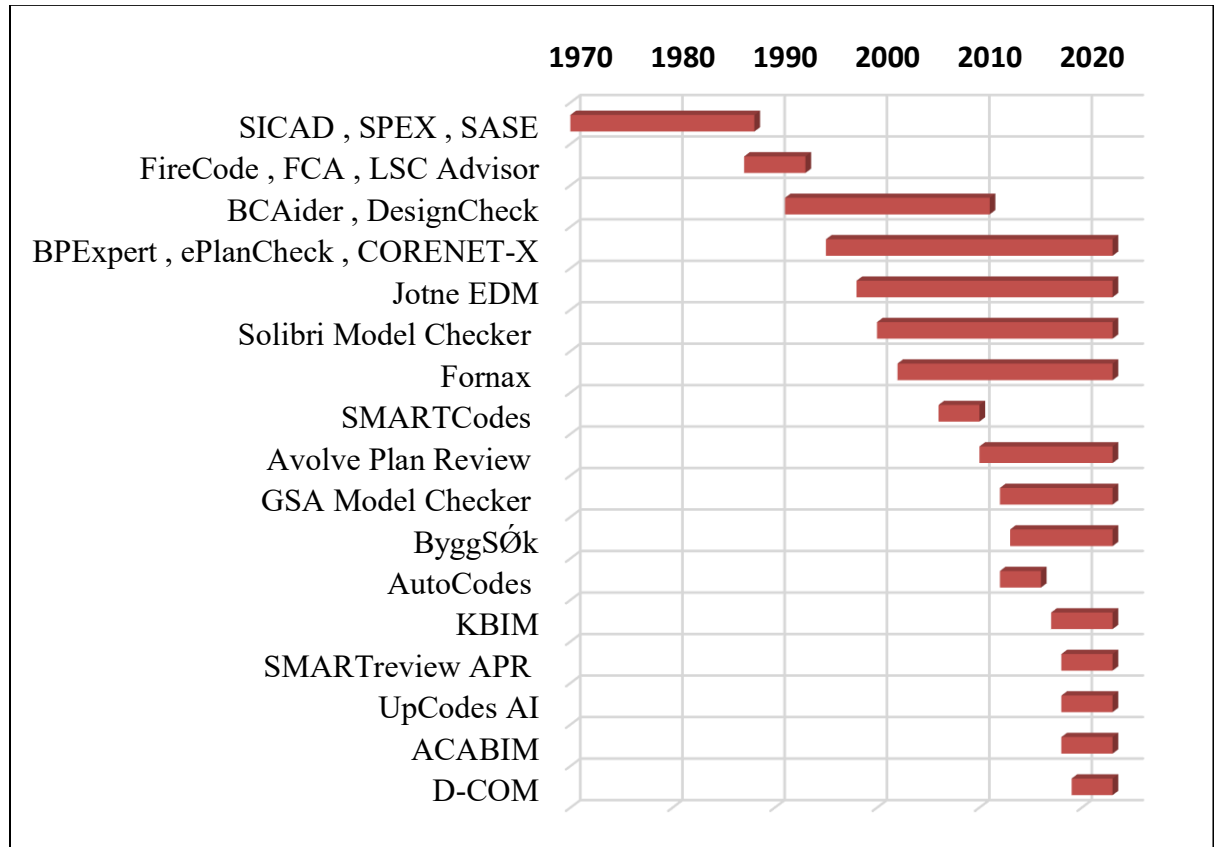


Figure 1 Timeline of major automated compliance checking.[31]

A critical challenge for every BIM-based Automated Code Compliance (ACC) system is aligning building design information from BIMs with fundamental concepts of building codes that underpin regulatory rules. The four-stage rule-checking framework proposed by Eastman et al. [32] consisted of (1) rule interpretation and logical structuring, (2) model preparation, (3) rule execution, and (4) reporting of results. In general, code compliance checking systems must automatically convert regulatory rules. For a successful conversion, accurate tagging of building code texts is essential. Previous experiments have shown that advanced generic taggers were not effective in analyzing building codes [33].

The goal of this research is to set up the basis for an automated code compliance checking system that can expand its scope of checkable code requirements with minimum human effort. It utilizes the Dynamo programming software embedded within BIM. The Saudi Building Code is used as a test bed to be automatically checked by creating a Dynamo script that analyzes specific BIM model elements to determine if they comply with local legislation. The result proposes a real-time decision-support tool that allows designers to check if their buildings are up in line with local codes, regardless of where they are in the design process. This facilitates collaboration, the incorporation of innovative ideas, and clear communication of code compliance. In addition to assisting local authorities in ensuring project compliance, this approach can cut down on assessment and calculation mistakes and the time spent on routine paperwork.

1.2 Problem Statement

Manual checking of design compliance with applicable building codes is an expensive, error-prone, and time-consuming process. Causes for these difficulties include (a) the large amount of data that needs to be checked and its multidisciplinary nature; (b) building code and standards are being updated more frequently to reflect new information and research; (c) the complexity of hardware/software communications is increasing and (d) cutting-edge technology, equipment, and devices are being more rapidly updated. Manual checking of code compliance in building design can lead to misunderstandings of regulations, inaccurate self-checking of required aspects before bidding, and financially detrimental delays in construction permit approval.

Existing methods for automated compliance are often proprietary or domain-specific and lack flexibility and generalizability. They are difficult to modify, costly to maintain, and induce struggle with the subjective and ambiguous aspects of building regulations. Managing ambiguous information in building codes poses a challenge that many existing

systems fail to effectively address. Unlike domain-specific or platform-specific methods, the proposed system in this research offers a more generalized approach applicable across different domains and supports open standards. The purpose of this thesis is to provide an analysis and solutions to the following research questions:

1. How can BIM models be structured to support building regulations checking?
2. How can automatic compliance checking systems of building codes be developed, scaled, and maintained?

1.3 Objectives

The goal of automating compliance checking in building design is to simplify the process and improve effectiveness. Converting regulatory statements into executable code using a standardized approach streamlines compliance and ensures accuracy. Furthermore, it is essential to create scalable systems that can effectively manage the complex rules of regulations. This research aims to:

- Develop a framework to automate the checking of design compliance with building codes, specifically, the architectural aspects of residential buildings in Saudi Arabia (SBC 1101- CR).
- Assessing the developed framework in practical scenarios using BIM and Visual Programming Language (VPL) to evaluate its effectiveness in automating compliance checking for architectural aspects of residential buildings in Saudi Arabia.]

1.4 Limitations

While this research makes a significant contribution to the advancement of automated code compliance (ACC) systems in the Saudi Arabian construction industry, it acknowledges several limitations that may affect its scope, applicability, and impact. These limitations highlight the need for further exploration and development. One primary limitation lies in the scope of the rule base. The research primarily focuses on quantitative requirements (30 rules) for architectural aspects of single-family houses (villas), which are widely applicable within Saudi Arabia. However, this narrow focus limits its application to other building types or more comprehensive regulatory needs.

The research also relies on the accuracy of input data. The effectiveness of the tool is contingent on the precision of the input data. Inaccuracies in the initial BIM model or data inputs can result in incorrect compliance assessments, potentially undermining the system's reliability. Additionally, there are geographical constraints. The focus on Saudi Arabia's building code may restrict the applicability of the findings to regions with different regulatory environments, limiting its global relevance. Another notable limitation lies in the challenges of rule interpretation. Although the study employs semantic markup techniques, such as RASE, to interpret building code rules, some regulatory clauses remain ambiguous or require subjective judgment. These ambiguities result in a compliance-checking process that is semi-automated rather than fully automated, necessitating human intervention during data extraction and rule interpretation.

1.5 Significance of the Research

Innovations in the fields of the AEC industry are constantly and rapidly progressing and expanding. Most of the code compliance checking, which is both laborious and intricate, is currently performed by hand. The incidence of undesirable errors is increasing, and the project is halted whenever the structural code-checking system detects them, which is a time-consuming process. The goal of this research, which draws from a variety of disciplines, is to help the AEC industry with certain real-world issues by combining fields such as law, informatics, and construction domains.

Experts in construction and law can steer progress with this approach, minimize the reliance on external consultants for supervising system development. Construction and legal professionals can assist in understanding regulations and minimizing consultancy expenses by real-time decision support tools to ensure their constructions meet local building standards, assisting municipal authorities in validating project adherence, minimizing errors, and streamlining project assessment procedures.

This approach can help discover which regulations or sections of regulations can be written as computable rules, depending on the advanced method. This ranges from simple transcribing (e.g., door opening ≥ 1000 mm) to help from expert systems. Identifying the degree of digitization before commencing a development project reduces uncertainty and sets realistic expectations. The methodology offers a practical framework for interpreting qualitative statements in performance-based regulations, focusing on specific building types and complexity. It organizes regulations into tables or databases, identifying which regulations apply in specific situations and with specific requirements, thereby enhancing the understanding of regulations.

Economic impacts of Automating Building Permit Procedures, by Hjelseth [34] defines four critical aspects: First, there is a direct impact from understanding and applying regulations. Second, automation reduces uncertainties in permit processing, leading to predictable outcomes. While automation provides quick results, manual methods with digital guidelines are still viable. Third, automation brings additional benefits, like more design choices and better compliance assessments. Lastly, the fourth aspect highlights cost implications, especially through BIM-based checks that can efficiently analyze multiple projects, improving the quality and content of BIM files.

This method necessitates alignment between required processing information and BIM file content for reliable checks, though its increased adoption can foster the utilization of BIM-based model checking systems. It lays the groundwork for the development of computable rule systems that align with the strategic objectives outlined in Saudi Arabia's 2030 Vision for the construction industry. By promoting advanced automation tools like building code compliance software, this research aims to expedite the building design process, thus supporting the nation's strategic goals.

1.6 Thesis structure

The structure of the thesis is organized as follows:

The first chapter introduces the research objectives, scope, and significance. It emphasizes the need for automating building code compliance processes in Saudi Arabia, focusing on architectural aspects and residential buildings. The chapter discusses the challenges of traditional compliance methods, including inefficiencies, inaccuracies, and the growing demand for digital transformation in the construction industry.

In Chapter 2, it explores existing methodologies for automated code compliance, including logic-based, language-based, and ontology-based techniques. It discusses the limitations of current systems, such as their focus on machine understanding at the expense of user interaction. The chapter also highlights the relevance of BIM and VPL in developing effective compliance systems and positions in this study within the context of global trends in digital construction.

Chapter 3 presents the methodology and framework for developing the ACC system. It outlines, existing Methods: A review of manual and semi-automated permitting systems in Saudi Arabia , framework Development: The use of Design Science Research (DSR) methodology, emphasizing rule representation, data collection, and the use of semantic markup (RASE) for digitizing the Saudi Building Code (SBC), key Components: Steps include interpreting rules, identifying BIM properties, testing rule execution, and validating the framework. The chapter provides a detailed explanation of how the framework integrates BIM, VPL, and regulatory rules into an automated system.

Chapter 4 discusses the implementation of the ACC framework that involves integrating regulatory rules into BIM environments, creating automated workflows for compliance checks. Case Studies: Application of the ACC system to hypothetical and real-world residential projects to validate its functionality , modeling Guidelines: Recommendations for creating BIM models compatible with the ACC system, including specific naming conventions, property definitions, and compliance parameters, rule Execution: The use of Dynamo scripts within the BIM environment to automate compliance checks against SBC requirements, and compliance Reporting: Development of real-time compliance reports in formats accessible to users, enhancing transparency and decision-making.

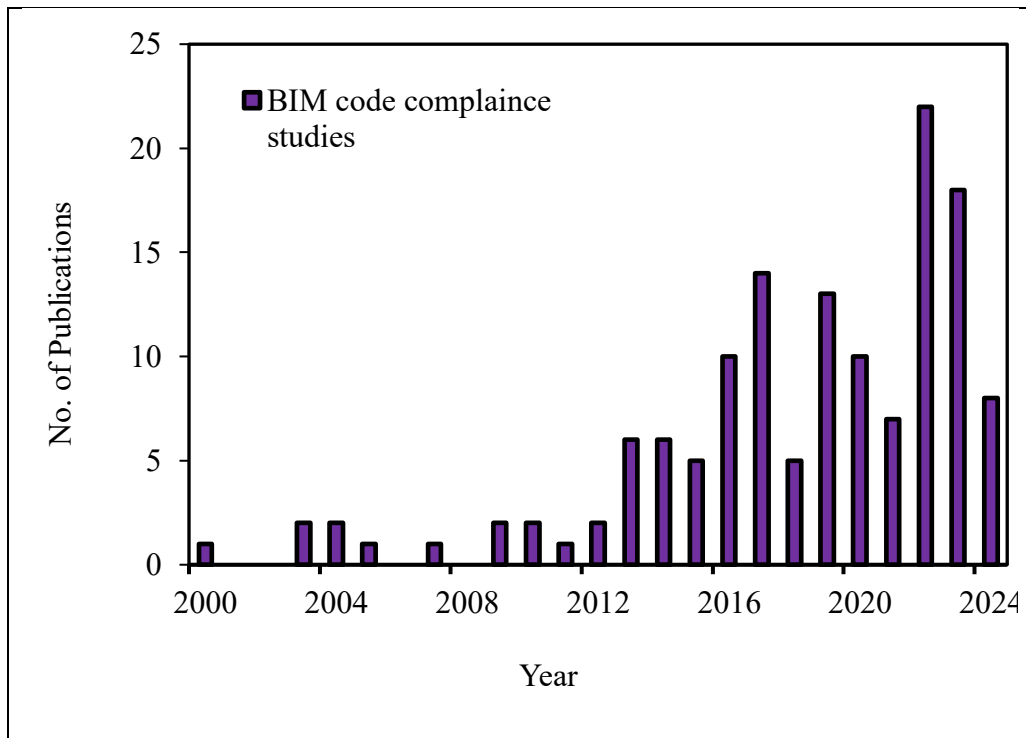
The final chapter proposes the summary of this research and areas for future research, including expanding the system to include qualitative compliance criteria, such as aesthetic and cultural considerations; integrating advanced technologies like Artificial Intelligence (AI) for rule interpretation; adapting the system for structural, mechanical, and environmental compliance; enhancing interoperability with other software tools; and exploring cross-border applications to standardize automated compliance verification globally.

[CHAPTER 2]

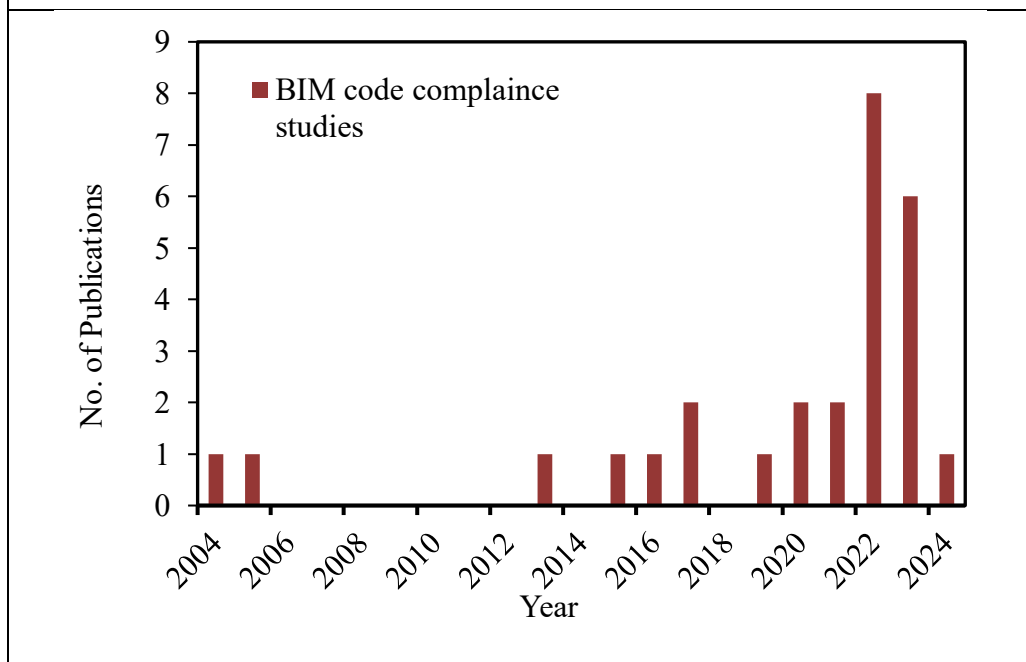
[LITERATURE REVIEW

For decades, researchers have been attempting to find ways to automate the processes of testing for compliance that are essential to planning, design, building, and operations. As computing and related technologies have progressed, the literature has shown that substantial research effort has been conducted, with various levels of success. Recent developments in theoretical and applied computing, along with high industry demand, have created opportunities that have the potential to make this quest a reality. This study analysis reveals the general relevance of finding a research gap and systematizing existing information under the development of a basis for a conceptual model.

This research focuses on articles published between November 2019 and March 2024. It used advanced research in major international electronic scientific databases such as Science Direct, and Scopus. The searches were conducted by applying relevant keywords in the Title, Abstract, and Keywords sections of these databases.



(a) Scopus data, keywords: building information modelling; code; compliance; search in Abstract, title, and keywords.



(b) Scopus data, keywords: building information modelling; code; compliance; search in title.

Figure 2. Scopus data, keywords (a), (b).

The research used the key words "BIM-based model," "automated code compliance checking," "building codes," and "building compliance," and found 145 articles. Figure 4 illustrates concept map revolves around the main theory and method discussed in papers, which this paper will also explore. Figure 3 highlights the distribution of documents across several academic or research disciplines. The engineering sector, comprising 44.1% of the pie chart, is the most extensively explored area within the dataset, evidenced by a substantial number of documents in this category. Furthermore, computer science constitutes 25.6%, rendering it the second-largest discipline represented, albeit marginally smaller than engineering.

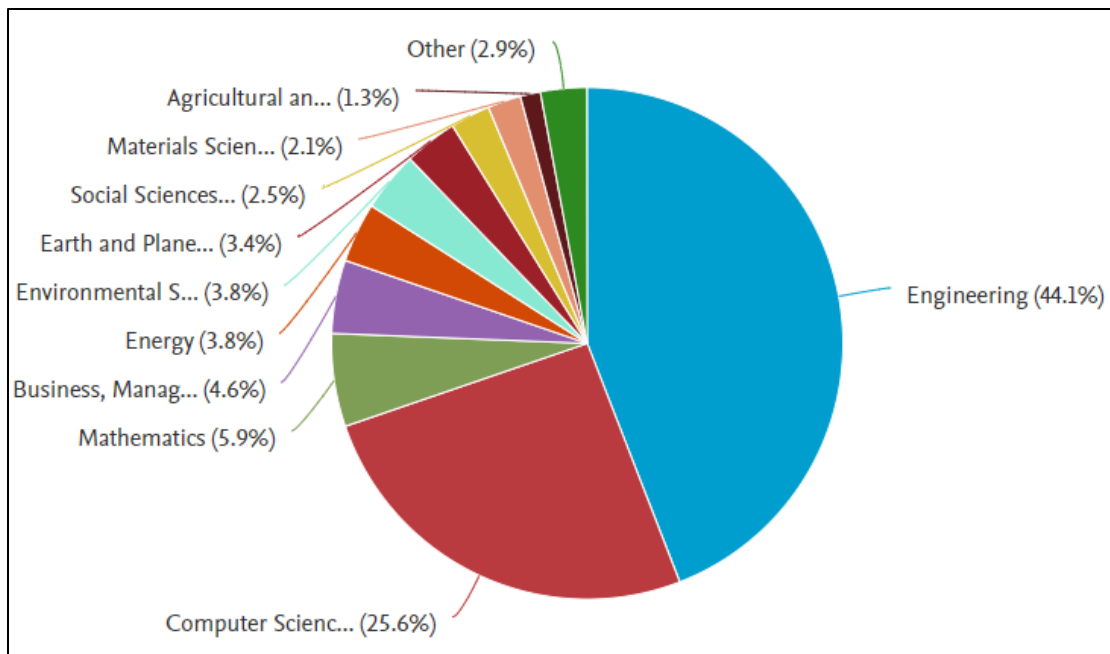


Figure 3. Distribution of Documents by Academic Discipline

Figure 3 illustrates a concept map derived from the literature in this part, emphasizing Building Information Modelling (BIM) and its interrelations with many subjects in the construction and compliance domains. BIM functions as a central repository for critical processes, including Industry Foundation Classes (IFC), both automated and manual

compliance verification, sustainability efforts, and building safety standards. The next subheadings will present this map, which categorizes the papers based on their focus areas and approaches. It additionally categorizes the documents into the present status of automated compliance verification, the methodology for processing normative requirements as computable rules, the challenges associated with the exchange of digital architectural, engineering design information, and strategies for overcoming these obstacles. It showcases the latest innovative strategies, examines the challenges faced by national projects, and delineates prospective future directions.

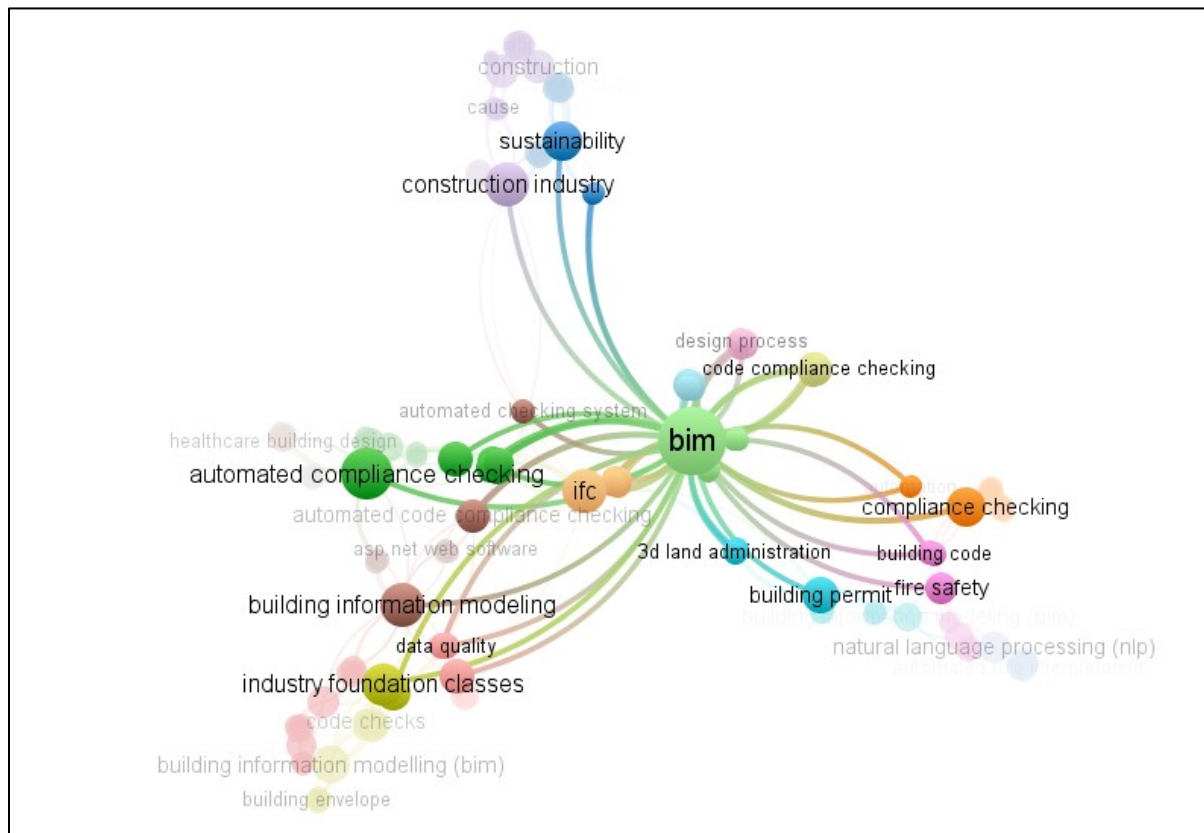


Figure 4. Visualization map for main themes of this paper.

2.1 BIM technologies & methodology for compliance

BIM technologies and methodology are increasingly facing compliance challenges, including the automation of procedures pertaining to regulatory matters, visual language strategies, industry foundation classes, automated code verification, and more methodologies. Numerous research projects and certain proofs of concept demonstrate significant advancements in this domain, enhancing efficiency and rapidity in the verification of regulatory requirements. A summary of some intriguing methods and methodologies is provided below:

2.1.1 Visual Language Approaches

Visual Language Approaches (VLA) are prominent due to the limited programming background of many AEC practitioners. VPL has been recognized as a user-friendly coding mode in comparison to conventional text-based programming languages [35], [36]. It enables programming using a two-dimensional notation that utilizes visual elements instead of textual ones, resulting in simpler and faster interpretation [35]. By integrating with various BIM platforms, VPL offers an extensive amount of control and customization over BIM models. This is related to its geometric modeling capabilities and algorithm creation abilities [37]. The use of VPL offers transparency, flexibility, and portability because design rules can be read by both machines and humans [38].

Rule verification has become an important topic in the use of VPL in recent years. This is because the process involves repetitive tasks that can be efficiently automated through appropriate codification [35]. Cavalliere et al. [37] have developed a new method using VPL assessing building adaptability throughout the design process. This method automates design rules into six specific criteria, providing real-time data for decision-making related

to flexible and sustainable choices. Moreover, Villaschi et al. [39] built a VPL framework on Dynamo, thus automating the verification of Brazilian building prescriptions against the design—which provides a tool that had not previously been available in this field for such compliance to be appraised by the evaluators and the authorities.

Additional BIM-based VPL methods involve utilizing Dynamo to manage and rectify inaccurate analytical data derived from BIM geometries, thereby improving the process of generating a Finite Element Model [40]. Other uses for structural analysis in buildings have been demonstrated by Sheikhhoshkar et al. [41] through the extraction of spatial data pertaining to construction joints from BIM models using Visual Basic for Applications VPL, Matlab, and Excel. Banfi and Previtali [42] utilized VPL and a 3D real-time platform to achieve extended reality for the examination of archaeological sites and heritage buildings. Other techniques that have been utilized include scan-to-BIM and digital photogrammetry. Like how VPL is developing for topics like facility management, it integrates BIM models, databases, and sensor data through multiple links[36].

Kim et al. introduced the KBim Visual Language in 2019, which is based on KBimCode and is used to interpret Korean design codes through visual symbols. KBVL allows various users to perform building code compliance checks using KBimCode Figure 5. Visual symbols are utilized to simplify intricate regulations, enabling individuals with minimal programming knowledge to conduct automated rule checks. The Korea Building Law (KBVL) was designed with more than 15,000 sentences to identify elements for generating building regulations.

The components are categorized into three types: building objects, checking methods, and reference and delegation information. The components are stored in the KBim meta-DB, where they are managed and regularly updated with new data. Users can select functions and regulation actions for their building code as needed, which minimizes errors from using improper methods unrelated to building rule verification and improves the automation of rule verification in the construction sector.

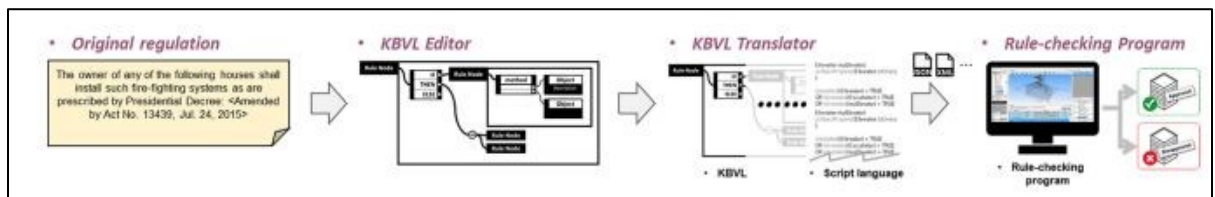


Figure 5 flow and process of KBVL.

Ghannad et al.[43]introduced a modular framework for code interpretation and representation that integrates the VPL and open standards Legal Rule [44]. Haußler et al. integrated two models and notations to represent the railway design codes[45] .VLA-based representations are more comprehensible, user-friendly for designers and domain experts, and more effectively utilized in ACC for domains or checkpoints. Nevertheless, it encounters a similar issue to object-oriented representation due to the absence of class and event definitions in the code representation, leading to illogical structure and confusing relationships.

2.1.2 Industry Foundation Classes

Industry Foundation Classes (IFC) is a data model that is open internationally and standardized by ISO 16739-1:2018. Its purpose is to facilitate interoperability between different software applications used in the various participants in the construction or facility management industry, specifically for building information modelling [36].

BuildingSMART International developed and updated the IFC schema specification, which was ISO certified in 2013 with the International Standardization Organization to promote openBIM® [37].

The introduction of the BIM idea, along with the IFC open data format definition for building components, established a standardized approach for creating a computer-readable representation of a building and a universally accepted protocol [46]. There have been significant advancements in automated code compliance testing since the IFC open data standard for BIM appeared[47]. Programs built on the BIM platform can support IFC to a specific commercial transaction, it is commonly used to transfer data between parties [48]. The AEC parties and asset managers can share data more effectively with the use of the IFC system. Sharing data in a way that facilitates and encourages interoperability is a major reward of the IFC concept. **Figure 6** shows a few features that can be implemented with the help of the IFC method for data sharing.

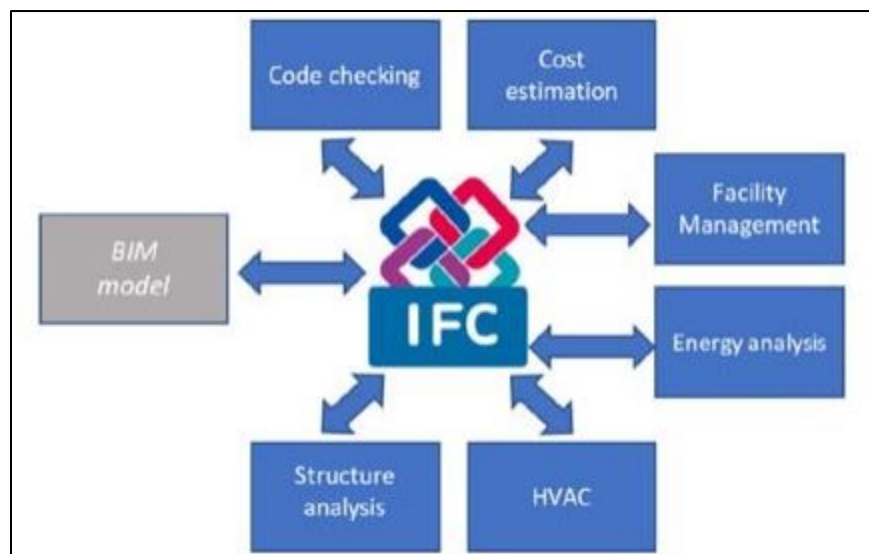


Figure 6 An illustration of the benefits of interoperability linked to the IFC scheme[49].

Building designs in the AEC domain are subject to many rules and requirements, including specifications, building codes, and standards. Building code compliance is the primary goal of ACC systems. However, one obstacle is the lack of a common language between BIM and codes. Current methods necessitate manual data alignment, which is inflexible and not easily transferrable to other contexts[50]. By studying the syntax and semantic patterns of IFC data and regulatory text, machine learning models can automate this procedure[51]. BIM systems employ the IFC standard for data representation and sharing in AEC industry [52].

Temel et al.[53] studied using IFC within BIM to automate code compliance in the AEC sectors. They found that traditional manual methods are time-consuming and error-prone and proposed a solution using BIM technology. The study uses Autodesk Revit software to extract building data into an IFC file, reducing human errors and improving efficiency. The findings suggest that IFC could lead to more standardized, efficient, and cost-effective compliance processes.

Wang et al. [54]represented building designs in IFC format as graphs. They employed graph neural networks (GNN) to categorize the rooms in the IFC models into nine predetermined kinds. This classification was based on manually created node and edge attributes. Additionally, they enhanced the models by incorporating the identified room types. ACC systems face difficulties in aligning the semantic structure of BIM data in IFC format with the semantic structure of regulations expressed in natural language. Current approaches rely on manual labor and struggle to effectively manage intricate regulatory ideas.

Zhang and El-Gohary [52] proposed a deep learning technique to align semantic information in IFC regulation. The approach used a relation categorization model to establish connections and synchronize IFC and regulatory ideas. The system utilizes a transformer-based model along with an IFC knowledge graph to enhance the process of categorization. The technique was assessed using IFC 4 concepts and regulatory concepts from several building codes and standards, demonstrating a high level of accuracy in aligning information. The method uses a five-step process, including creating an IFC knowledge graph, developing concept pairs, and fine-tuning transformer-based models with domain-specific IFC data. The method outperforms traditional approaches and offers significant improvements in semantic alignment accuracy.

The research conducted in France seeks to utilize semantic web technologies to automate the process of conformity checks for building codes, with a specific emphasis on French construction rules[55]. The research presents a model that transforms unclear and intricate requirements into algorithms that can be executed, enabling the identification of non-compliance in building models. This procedure entails the transformation of Building Information Modelling (BIM) data into Resource Description Framework (RDF) format using ifcOWL. The objective is to enhance the compatibility and handling of data related to construction projects. Additionally, the methodology includes a modelling charter to establish a standardized approach for exchanging data among stakeholders.

Zhang et al.[56] introduced a novel machine-learning method to automatically associate building-code concepts and relationships with their corresponding IFC counterparts. Code BIM matching and alignment of concepts expressed in the codes with those in the BIMs are necessary for all these systems. Khattra et al [57]explored the utilization of building

information modelling to transform the process of designing buildings for structural stability. The authors presented a methodology that revolves around the Industry Foundation Classes for interoperability and automation, using a rule-based engine and Python scripts from the IfcOpenShell library in conjunction with FreeCAD software. Key findings indicate that this approach significantly reduces manual work, minimizes errors, and improves accuracy and efficiency in compliance with building codes such as the Indian seismic code IS 13920. The automated system highlights a novel capability to streamline the structural design process, enhance collaboration and information management, and represent a significant advancement in architectural and engineering practices.

Jin Wu et al.[58] conducted a study on enhancing the ACC of building codes using a new algorithm for identifying AEC objects. This algorithm uses invariant signatures derived from the geometry, position, and material attributes of building elements to automatically verify input design models. By utilizing the IFC format, the program converts these models into computable representations that facilitate ACC. The study employed the International Building Code 2015 to evaluate the effectiveness of this method, specifically examining the validation of ceilings and interior doors in a convenience store model.

Figure 7 illustrates the relationship between IFC and building code in which Inferable concepts are identified by recognizing related IFC entities and selecting those satisfying additional constraints based on heuristic rules. Heuristic rule-based algorithms are developed for each inferable concept, which are verified on training data. Inferable concepts, such as egress, can be identified automatically without human judgment. User-assisted concepts can be semi-inferable with additional user input, but not 100%. The boundary between inferable and user-assisted concepts depends on current implementation

and reasoning capabilities. System defaults are concepts not related to building codes but are still needed for logic-based reasoning.

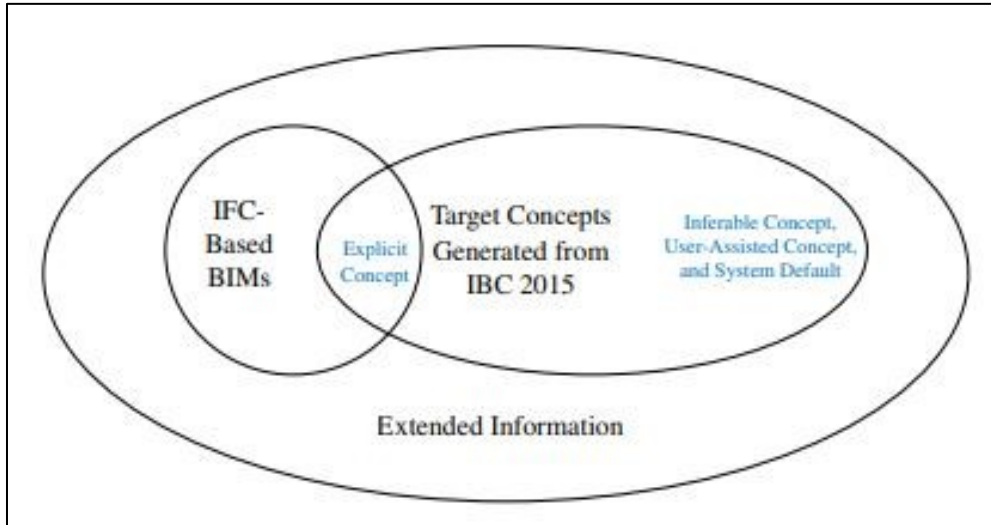


Figure 7. concepts in IFC models & building codes.

Noar do et al. [59] identified issues with existing IFC models and developed a semi-automatic tool to address them. These challenges include variability in model quality and content, a gap between theoretical use and practical application, a lack of standardization, inadequate semantic accuracy, and geometric and semantic limitations. These issues lead to a reliance on manual adjustments to make IFC models suitable for automated processes. This tool compensates for the variability in model quality and content by analyzing geometric and semantic data, identifying discrepancies, and allowing for manual oversight in cases where automatic processing is insufficient.

Ostashev [60] used IFC standards and BIM as a structured database for automated verification of environmental impacts in construction projects. To assess and mitigate construction activities, it employs algorithms to systematically check BIM attributes against environmental standards, focusing on specific attributes and property sets related

to ecological effects, including energy efficiency and resource usage. He ensured interoperability and facilitated the exchange of data across different systems. To prioritize the most impactful verifications, the approach includes a value calculation for each verification, considering environmental benefits and resource investment. An iterative validation process ensures data accuracy before proceeding with automated checks, enhancing the precision and efficiency of sustainability assessments in construction projects.

Nawari's[13] study aims to improve building design compliance by addressing the limitations of current automated design reviews, which are proprietary and domain-specific, as 'Black Box' or 'Gray Box' lack a generalized framework (GAF) or neutral data standard like the IFC. The GAF utilizes advanced technologies like Building Information Modeling (BIM) and Artificial Intelligence (AI) to facilitate the extraction, reasoning, and application of data at various project phases, enhancing communication and interpretation among stakeholders, thereby improving the quality and performance of construction projects.

2.1.3 Code checking using automated text

Recognizing relevant sentences from massive amounts of documents and putting them into one or more predefined categories is what the text classification task is all about it [53]. The current codes are written in natural language and primarily read and used by domain experts. Consequently, computers find it challenging to automatically comprehend, process, and analyze these codes [54]. Hence, numerous researchers have investigated automated methods for interpreting regulatory texts and converting them into a format that can be processed by computers.

These methods are used for automated compliance checking and even intelligent design[61], [62]. Numerous studies have concentrated on automated rule interpretation tasks utilizing natural language processing (NLP)[62]. For instance, many researchers have extensively studied data extraction and transformation[63], [64]. The process of data extraction and transformation begins with the identification and extraction of the appropriate words and phrases from the relevant sentences.

After that, the pieces of extracted semantic information are transformed into representations that computers can understand. Nevertheless, the building code is typically formulated in ordinary language and employed by human engineers who possess extensive expertise in the field. The presence of issues like incompleteness, ambiguity, vagueness, and implicit knowledge has posed challenges for computers in comprehending intricate building codes automatically[65].

A computer would not be able to automatically interpret all the requirements in the codes. It gets poor in interpretability when it comes to these criteria. A high number of mistakes could be produced by automatically interpreting requirements that are not very interpretable[66]. Guo et al. highlighted the application of NLP to extract rules from text-based regulatory documents and associate them with BIM data. As part of the methodology, semantic similarity analysis, term matching, and the creation of SPARQL queries are used to check for compliance. A case study demonstrates the approach's effectiveness in providing flexible and efficient rule checking for BIM data[67]. Another research conducted by Jin Wu et al discussed the development of a framework called the I-SNACC framework as shown in Figure 8, an advanced system for automated building code compliance checking. combining natural language processing and logical reasoning.

It uses Python for rule generation and Java for core parts, reducing fine-tuning time by 45.4%.

The framework finds non-compliances with 95.2% accuracy and 100% recall. A rule modification module, model validation using invariant signatures, and activation conditions using identified building design entities are some of the most important new features. The method worked well in a prototype setting, but more NLP improvements and code coverage are needed for its full potential[68].

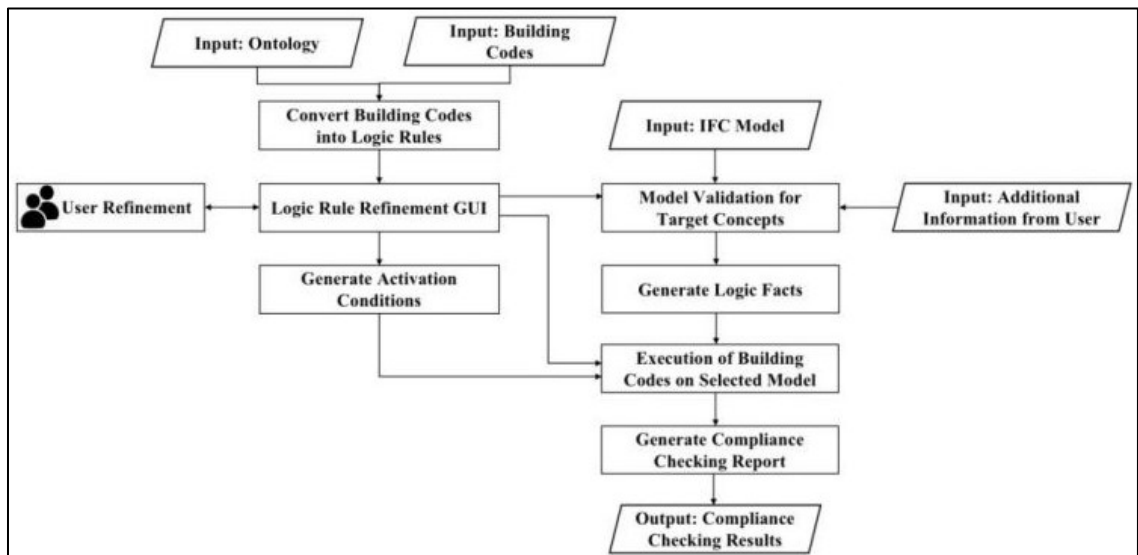


Figure 8. The workflow I-SNACC framework.

Yukang Wang et al. [69] had developed an innovative system that automates fire code compliance in building design using BIM and NLP. The system interprets spatial relationships in BIM models, allowing for a detailed review of building components in relation to fire safety regulations. BIM models are parsed to understand complex parts, fire codes are transformed into structured logical expressions using NLP, and compliance results are displayed visually. The approach categorizes code clauses into single, multiple, and compound judgments, improving accuracy and efficiency.

Hong Soon et al [70] explored the creation of a database to automate building code review in South Korea's predesign phase. They studied proposes a method to convert building codes from natural language into a readable computer format, enabling automatic review of building mass through an authoring tool. It places particular emphasis on those impacting building-to land ratio, floor area ratio, height, and other factors affecting the three-dimensional size and shape of buildings.

Thus, while previous research has made automated rule interpretation easier, most efforts in information extraction and transformation center on, easily interpreted clauses that have been manually filtered. Recent years have seen the integration of text classification into the automated rule interpretation pipeline, which further enhances the accuracy of data extraction and transformation. On the other hand, most current text categorization efforts sort clauses into categories based on their subjects, topics, or scopes[71] .

Purushotham et al.[72] have developed a method for automating building code compliance using a flexible BIM tool and NLP techniques. The approach converts building codes into machine-readable rules, enhancing rule accuracy and facilitating quick compliance checks. The system uses a semiautomatic, stepwise process, ensuring code integrity and context. The study shows significant improvements in transparency and efficiency, offering a scalable solution for integrating automated compliance checking into BIM applications and reducing compliance time.

2.1.4 Semantic and knowledge graph approaches

Beach et al. conducted a survey to find out the industry's perspective on ACC [66]. On average, "Lack of shared open standards for regulation clauses" was cited as the biggest

obstacle to ACC, while one-third of respondents cited "Lack of precise digitizable regulations" as an equally important obstacle. The barriers are primarily due to the inherent complexities of code clauses [67]. Complex clauses with multiple requirements are frequently found in design codes but are seldom discussed in relevant research [58].

Current approaches often manually process a small subset of code clauses in a few designated areas or employ a random sampling of code clauses with low complexity. Example: clauses that have been hand-picked or subclauses that have been deconstructed and contain solely binary semantics. Code clauses are still underappreciated or disregarded due to their structural diversity and semantic complexity, although some studies have used NLP-based automated processing of code clauses[73] . Consequently, one of the most important concerns with representing design code is making sure that complex clauses fully represent the semantic information[74]. Knowledge graphs (KG) will play a crucial role in knowledge management within the architecture, engineering, and construction (AEC) industry in the future[75].

Knowledge Graph (KG) is a human-recognizable, machine-friendly knowledge representation model [76]. It organizes data based on the directed attribute graph structure, which effectively reduces the complexity of representation model and provides greater flexibility and interpretability[77]. According to Wang et al. [78], the triple, which is the fundamental building block of KG's semantics, can faithfully portray the binary semantic for numerical and non-numerical classes within code clauses.

On the other hand, semantic information is more complicated than what the triple represents. An analysis of the Freebase KG entities revealed that over 33.3% engage in

non-binary relations[79]. And based on Fatemi et al.[80], 61% of the relations in the Freebase KG are non-binary. The KG model can be easily extended with the help of directed graph-structure-based data organization. By including more attribute-value sets to stand in for the n-ary relations, expanded the KG triple [78]. Li et al. discovered that the characteristics of the triples are beneficial for utilizing the medical KG. Therefore, they expanded the triples to quadruples by adding extra fields to accommodate information that cannot be expressed by triples [81].

Extended knowledge graphs improve the capacity to depict intricate semantics. After discovering that the medical KG might benefit from the triples' attributes, Li et al. expanded them to quadruples with extra fields to accommodate data that does not fit neatly into the triple format[82]. With these enhanced KGs, complex semantics can be better represented. There are two methods for constructing knowledge graphs (KGs). One method involves automatic construction techniques such as direct mapping for structured data [83], using wrappers for semi-structured data [84], and employing information extraction techniques for unstructured data [85].

The alternative method involves semi-automatically creating content by seeking input directly from domain experts using specialized collaborative-editing platforms. Yung et al.[74] propose a semi-automatic method for knowledge graph construction to allow the checking automation in compliance with the construction industry. The current models come with limitations and propose that knowledge be graph-based in structure and consider semantic interpretation and rebuilding. With the assistance of domain experts, the developed specialist annotation platform can be used to ensure accuracy, bridge gaps in existing models, and most probably improve upon existing models in respect to enhancing

precision and efficiency in compliance checking. Figure 9 below shows the model of design representation based on KG.

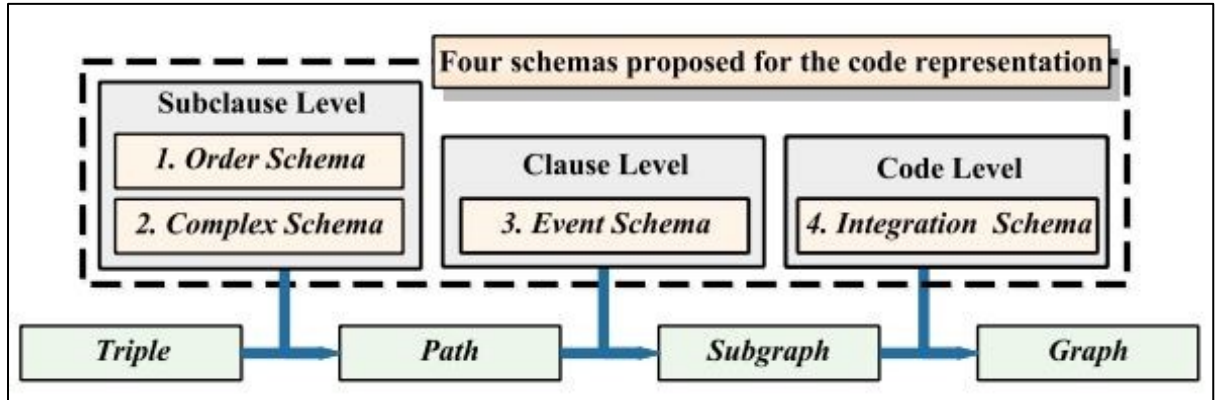


Figure 9 A model for representing design codes using knowledge graphs (KGs)[74]

Four schemas are recommended for the KG to ensure it represents accurately all the semantic types at the subclause, clause, and code levels. This paper proposes another parsing system which supports the original order schema, and the Complex schema developed for the representation of semantic information at the subclause level by adding a clause level schema, the event schema, to capture this hidden semantics and in turn logics. Further, the proposed integration scheme is to ensure an enhanced semantic model and a well-organized one at the code level. A special development annotation platform will help support the management and review of DCKG construction for automated compliance checking.

Yuhan Zhou et al.[86] have identified several challenges in facilitating knowledge transfer during code compliance checking using Conceptual Graphs (CGs). One of the fundamental issues is the difficulty in ensuring the quality of CGs due to their subjectivity, which can lead to minimal loss of knowledge. To address this, the paper proposes using reusable CG patterns to reduce the opacity of concepts in rules, known as "black boxes," which are the

main source of knowledge loss. By minimizing the proportion of black boxes, the paper aims to improve knowledge transfer using CGs.

The CG serves as a communication tool between rule experts and rule implementers as shown in Figure 10, helping them check if they understand the meaning of the code. In practice, building codes can be transferred and documented in two modes: an original rule description and a rule-interpretation document. The rule-interpretation document provides schematic diagrams and implementation scenarios for rule implementers to understand. The study validates this approach using building codes, demonstrating the effectiveness of CGs in transferring knowledge and streamlining the creation of new CGs.

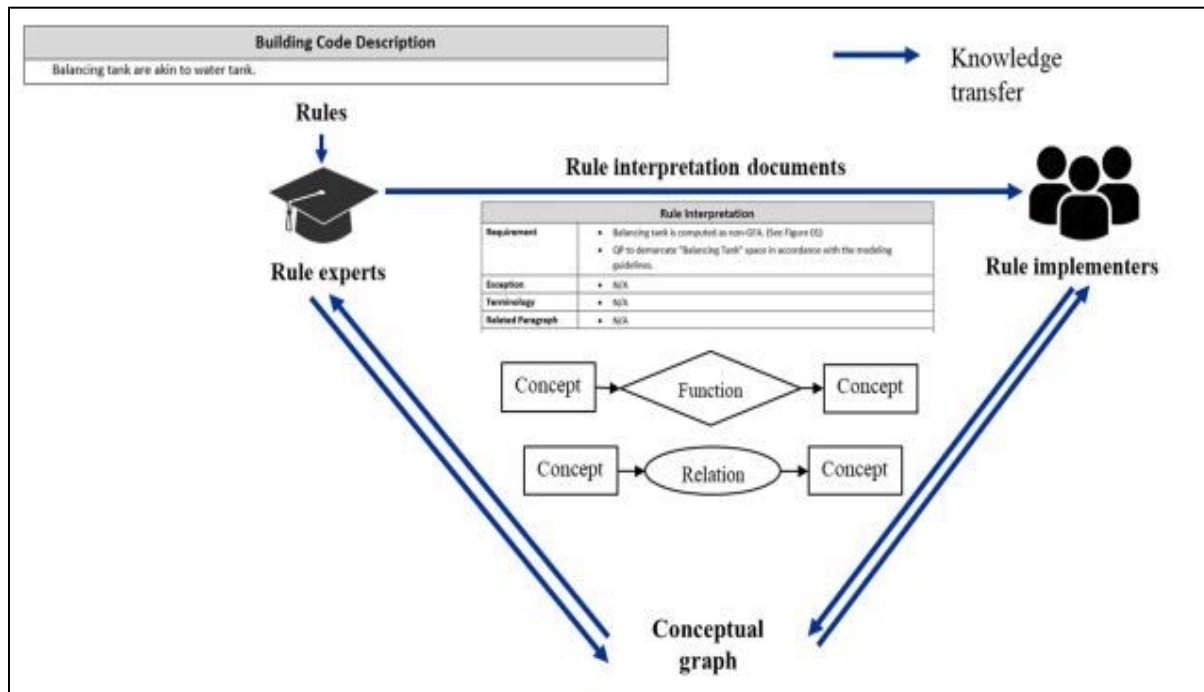


Figure 10 Transferring knowledge from rule experts to rule implementers during the interpretation of rules[86].

Zhang et al. introduced a semi-automated healthcare Knowledge Graph (KG) framework and created a platform to aid in KG construction by integrating clinicians' expertise into the health KG [87]. Tang et al. created a semantic annotation platform to construct a high-

quality legal Knowledge Graph (KG)[88]. Human experts' involvement ensures the high quality of Knowledge Graphs. Participation from stakeholders in the development of KG will help to fully utilize the advantages of KG in knowledge representation and interpretation[82].

Messaoudi [89]utilized the GAF technique to demonstrate the creation of a virtual permission process for the state of Florida. A virtual permitting framework utilizing BIM is developed based on an investigation conducted with local stakeholders. This work was subsequently expanded and implemented in the context of post-disaster recovery.

2.1.5 Ontologies for BIM Compliance Automation Checks

An ontology is a structured framework and systematic for representing knowledge in a particular field through a collection of related ideas, attributes, and relationships [85]. The benefits of establishing a common body of knowledge across domains and standardizing how different data models are understood have led to the introduction of ontologies as a tool for enhancing domain knowledge sharing and reuse [86], heterogeneous data integration [87], business management [88], and many more.

Code ontology is the foundational body of platform knowledge. Stanford University suggests an iterative approach to ontology creation that consists of seven steps [90]: domain determination, reusing existing ontologies, enumerating important terms, defining classes and classes hierarchy, properties, and creating instances of facts definition. The code ontology in this research is created following a five-step development roadmap that is based on this seven-step method as shown in **Figure 11**.

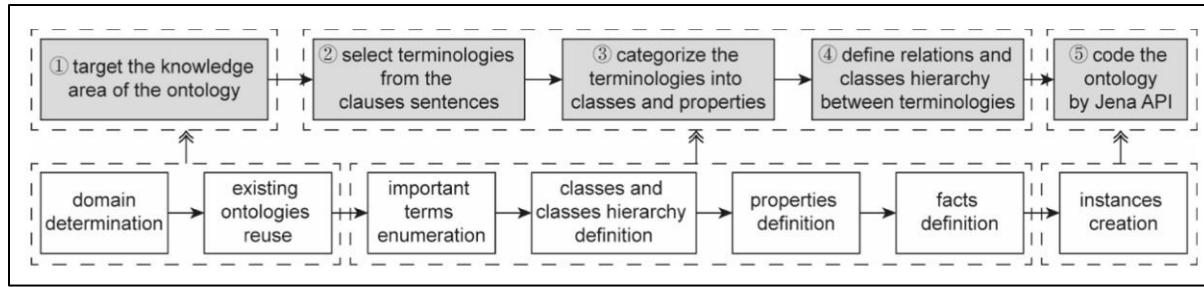


Figure 11 Five stages for creating a code ontology[90].

Liu Jiang et al.[91] propose a method that uses ontologies to automate the process of BIM to make the process ACC efficient. This strategy involves the development of code ontologies that provide organized and systematic information about regulations. Create a conceptual framework for designing models, known as design model ontology, which consolidates design information extracted from BIM models into a unified ontology. The code and design model ontologies are merged, and the rules are verified to automate the process of verifying compliance. Apache Jena manages ontologies and uses rule-based reasoning to resolve semantic differences between regulatory codes and building design information.

Zentgraf et al. [92]presented a methodical approach to creating a semantic framework for BIM. It develops an ontology based on ISO 23386 standards, aiming for seamless information exchange and automated compliance checking. The ontology is machine-readable, dependable, and meets standards for clarity, consistency, and reliability. Tools like Protégé, NLP frameworks, SPARQL endpoints, and SHACL validation tools are used to Linked Building Data (LBD) ontologies.

Bloch and Sacks [71] proposed the use of artificial intelligence to automate model preprocessing through semantic enrichment. Using clauses taken from different building codes and the k-means clustering algorithm, they organized and grouped semantic

enrichment tasks into a hierarchical structure. This process produces ten separate tasks that are essential for guaranteeing compliance. The tasks involve creating geometric representations, linking building elements, assigning property values, aggregating, and grouping elements, identifying objects, correcting errors, semantic tagging, defining spatial relationships, calculating compliance parameters, and normalizing data inputs.

Yuchao Li et al. [93] proposed a semiautomatic method for developing code ontology in railway engineering, leveraging Industry Foundation Classes Web Ontology Language (ifcOWL). This method consists of two main steps: adding new attributes and properties to the rail engineering code semantics and turning the extended ifcOWL into a hierarchical code ontology. They suggested implementing tools like Protégé, semantic web reasoners, and SPARQL queries. The method's success in railway code checking demonstrates improved extensibility and reduced manual input requirements.

The domain of building specifications is extremely specialized and involves plenty of sophisticated meaning [94]. The establishment of a specification ontology becomes more challenging as the specification becomes more complex. Considering ontology reuse is a crucial step, as stated in both Ontology Development and the METHONTOLOGY method [95]. The definition of taxonomy and attribute relationships becomes easier when existing ontologies can be reused or extended [96].

Patlakas et al. [97] have developed a new method for ACC by integrating Finite Element Analysis (FEA) with a Semantic Web-based system. This method, which uses the Industry Foundation Classes (IFC) schema and Web Ontology Language (OWL), streamlines compliance verification of structural engineering designs, particularly modular steel

structures. The system automates compliance checks against structural design codes, improving efficiency and accuracy, indicating potential for broader application in the AEC sector.

2.2 Emerging BIMs trends and innovations

2.2.1 Advancement methodologies in automated code compliance checking

Several studies have suggested novel modeling languages for interpreting and representing buildings code. Schwabe et al. utilized the Drools language to analyze and depict the code clauses, along with the four-level classification and RASE semantic tags[98]. Research presented a 'white box' computational workflow utilizing Rhino. Inside, Revit and Grasshopper enhance building code compliance checking in the architecture and construction industries. The workflow, which uses vector-based detection, reduces errors and delays by identifying non-compliant elements during the construction phase.

The methodology is based on action research and validated through real-world testing with industry-standard models from HDR Architects[99]. Soliman-Junior et al. [65]utilized Design Science Research (DSR) to automate compliance checks in healthcare facility design. Focusing on enhancing efficiency and quality, it develops taxonomy to classify regulatory requirements and explores the potential for automation, particularly in requirements with low to medium logic complexity. Key findings from testing with Solibri Model Checker indicate the feasibility of automated verification but also highlight the need for further refinement. Xiaoye Cai et al illustrated a software-assisted framework for implementing mode-based control algorithms in Building Automation Systems (BACS), addressing challenges in manual planning and implementation[one hundred].

Yogana Endiq et al [101]discussed a solution that integrates a building model developed in BIM with Work Breakdown Structure (WBS) in a single database. This integration allows for the dynamic management of building technical requirements and the automation of regulatory compliance checks. The system translates complex legal and technical building requirements into a BIM component, which is then verified through a web-based information system that has been validated by the government.

This system aims to facilitate the independent examination of regulatory requirements by planners at each stage of BIM model development. Additionally, research[33] presented a methodology using GATE to preprocess building code documents, utilizing the ANNIE POS tagger for [33]linguistic annotations. The text is then analyzed using an expanded ontology, identifying relevant concepts, and categorizing information. The method makes pattern matching-based rules better. These rules are then tested and changed to reflect code requirements more accurately in automated compliance checking systems. The iterative process reduces manual effort and improves accuracy and recall by 10.44%, 25.72%, and 18.02%, respectively, when tested against the International Building Code 2015. The textual structure of code clauses is best represented by semantic tags or open standards when modeling them. The text's complex semantic types and inconsistent syntactic structures make it hard to represent design code consistently and without duplication.

Yelin Demir et al [102]discussed automating zoning code compliance checking in building permits using BIM building information modeling and GIS geographic information systems. It highlights the shift towards digitalization in the AEC/FM industry and the need to combine detailed building data with neighborhood scale data for efficient regulatory compliance. The paper discusses the challenges of BIM-GIS integration, including data

conversion, model extension, and unified domain models. It also discusses the lack of standards and digital solutions that meet regulatory requirements by using a comprehensive literature review.

Beach et al. [103] have developed a new ecosystem approach to improve automated compliance checking in the construction industry. To address fragmented processes and a lack of integration technology, the system incorporates software tools. The study focuses on UK rules related to energy, accessibility, and fire safety. The prototype ecosystem includes core services such as compliance document services, result services, and rule engines, which enhance scalability, extensibility, and automation. The system's effectiveness was confirmed through a demonstration in a school building.

Li Xiaojun et al. [104] developed an intelligent construction system for Tunnel Boring Machine (TBM) operations, enhancing safety and efficiency. The system uses big data-driven models and automated compliance checking to collect real-time data, optimize TBM construction strategies, and ensure compliance with construction codes. Implemented in the PRDWRA project, it improved tunneling performance, reduced cycle time, and reduced costs, highlighting the importance of data-driven models in TBM operations.

Nuyts et al. [105] conducted a thorough evaluation of ACC methods for construction data. They compared eight approaches, including IFC standards, JSON Schema and XSD, and four Linked Data approaches. The study analyzed five categories of accessibility constraints from Flemish building regulations: information availability, value, relational, mathematical, and conditional. The study identifies Linked Data approaches, particularly

SHACL, as promising for construction data validation, though none fully meet automated compliance checking criteria.

In 2022, study by Fauth & Soibelman [106] compared the construction permit processes in Germany and the United States. They found that manual systems were inefficient and concluded that digitalization is necessary. The comparison between by-right and non-by-right situations highlighted significant distinctions, such as the United States' stringent segregation of planning and building regulations and Germany's comprehensive and unified approach. The authors propose the implementation of standardized and automated procedures to enhance efficiency and transparency. They argue that the experiences and insights gained from both countries can serve as valuable guidance for future enhancements in the building permit processes.

Al-Maabreh et al. [107] developed a framework to automate the evaluation of BIM data for disaster resilience, focusing on flood-related regulations. The framework identifies forty-two essential rules for flood-prone buildings, such as elevation, freeboard, openings, and breakaway walls. By integrating these rules into a web-based BIM validation system, the authors demonstrated improved accuracy and efficiency in compliance checking, enhancing single-family homes' resilience against floods.

2.2.2 Innovation in BIM for enhanced code compliance checking

Construction professionals have been writing and interpreting rules and regulations in codes for many years [32]. However, these codes were not specifically designed to be easily translated into computer programs. Moreover, novel criteria consistently arise across a wide array of disciplines [108]. There have been multiple attempts to implement code

checking on building representations (i.e., models and drawings) since computer- aided design (CAD) became popular in the 1980s. These representations use textual descriptions and specially coded drawing structures [32]. Researchers utilized knowledge-based methods to address ACC in CAD drawings and models. In 1995 Delis was employed a knowledge-based expert system to encode fire safety requirements and assess a design for overall compliance[109]. Previous research conducted around building code standardization also contributed significantly to these early endeavors, laying the groundwork for subsequent ACC studies that utilized building information modeling (BIM)[110].

BIM is known as a technology for simulating prototypes. The US National BIM Standard[111] defines BIM as the digital representation of a building project's physical and functional characteristics. BIM was introduced in the 1970s and has been extensively analyzed by researchers in various publications. Since the 2000s, the importance of BIM technology has gradually increased[112]. Collaboration between parties and information exchange is facilitated through the development of Industry Foundation Classes (IFC), a neutral file format used in BIM software [113]. This has enabled automatically generated parametric designs as well as automated compliance checking of those designs. The use of IFC has led to improved collaboration through shared information and automated processes like parametric design generation and rule-based design reviews.

BIM offers a promising avenue for expanding the application of ACC by facilitating regulatory compliance checks based on the attributes and relational information of building objects across fields. An example demonstrates the feasibility of mapping BIM model information to rules using a knowledge graph approach. Peng et al. [114] addressed issues

of dependency on manual review and inefficiency, solving problems in the current compliance review process. The main goal is to enhance the review process of converting specification requirements into a structured language that is understandable to computers and sharing review information from BIM models. Furthermore, the algorithm for model and rule code uses a modular approach, mapping through SPARQL queries and external programming. The system has a grid structure divided into data, service, application, and access levels. It aims to transform specification provisions into easily understandable structured language and export BIM model information for efficient and accurate review.

Automated code compliance checking plays a significant role in advancing the construction industry. Traditionally, compliance review relies on domain experts, but a study in Protégé aims to realize automatic review using BIM and knowledge graph technologies. The method transforms specification provisions for drawing reviews into a structured, machine-readable knowledge graph pattern using natural language processing [114]. For BIM model reviews, model information is exported to obtain a global resource description framework.

Ismail et al[115] reflected-on problems that arise when trying to develop automated code compliance checking systems that are increasing in complexity. They were focusing on developing a user-friendly automated code compliance system in Malaysia for fire safety regulation requirements. They translated 256 pieces of fire safety clauses using a semantic rule that was created using logic-based methods. Its concept was proven with a prototype model using a visual programming language. It is intended to allow easy access and practicality for designers using the native BIM model data representations.

Similarly, the study by Lee et al[116] gives methods that can be implemented at a high level to improve rule-checking procedures, considering that translating natural language into explicitly defined rules is a time-consuming and error-prone task. The approach focuses on the translation of verb phrases into building act sentences with minimal ambiguity, representing the peculiar properties of building objects without conflicts. The paper demonstrates the application of those methods in code compliance checking using KBimCode and developed rule-checking software. In contrast to logic-based methods, Gao & Zhong [117] propose a different approach with a blockchain-based framework Figure 12 for improved traceability, transparency, and management within the BIM-based building code compliance checking workflow.

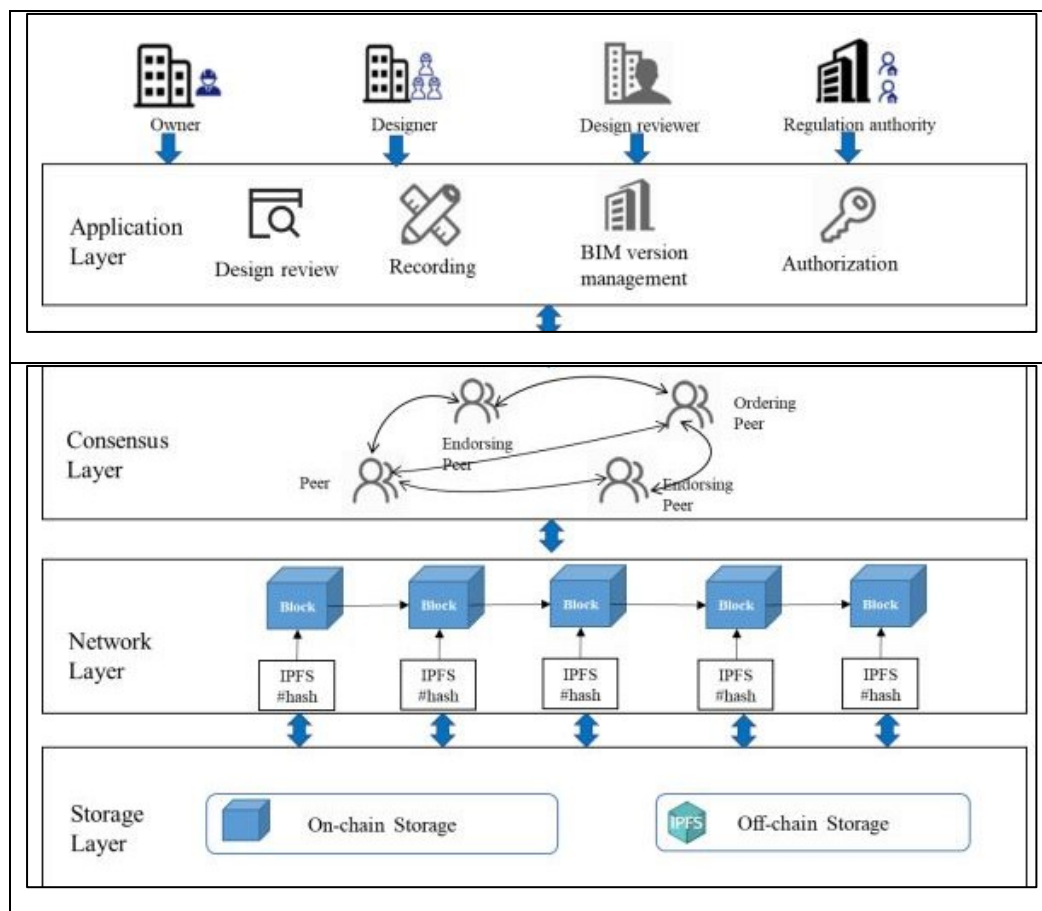


Figure 12 Blockchain-based system[117].

The goal of the framework is to integrate automatic and manual compliance review processes in the BIM environment that are responsive to issues raised in relation to data manipulation and human intervention. More so, they addressed some challenges that were met during the design review process, which included a lack of transparency, the risk of collusion, and data security concerns. Building information modeling and automated code compliance checking technologies are enhancing construction industry productivity and regulatory adherence, offering new opportunities for innovation and improvement.

A case study for Brazilian buildings [118], uses BIM and Dynamo software to automate urban indices compliance verification for buildings. It involved translating building code requirements into software code, creating an Autodesk Revit BIM model, developing a Dynamo routine for data collection and analysis, and generating a compliance report that meets local code requirements. Another case study integrated in the Building Sustainability Assessment (BSA) methods with BIM in a new tool called SBTool to automate early project sustainability evaluation. The research uses VPL to translate sustainability assessment criteria requirements into computable rules, creating the application. It used nineteen criteria from BSA and found connections for the other criteria to make an evaluation easier [119].

Paskoff et al. [120] presented a comprehensive, iterative BIM-based checking method for the mass timber construction industry. They proposed a systematic approach that started with interviews with industry professionals to address the problem. The method was developed through iterative development and validation using three model-checking case studies, including specification checking, digital environment implementation,

requirement interpretation, calculation, and compliance analysis to validate the application of a digital model for a building.

Murat Aydın [121] had conducted research aimed at enhancing the compliance checking of housing projects in Türkiye, particularly for the Planned Areas Zoning Regulation. It incorporated Building Information Modeling (BIM) technology alongside Asp.net Web software. The system employed C+ programming to convert building codes into operational rules that can autonomously verify building models against regulatory demands. The paper described how BIM-based ArchiCAD software reduces errors and compliance check time on a housing project.

2.3 Challenges and prospectives

Compliance checking in the construction industry involves ensuring building designs meet regulatory requirements, a complex process involving designers, domain experts, and regulators, reducing project delays and mediocre performance [122]. Researchers and practitioners have developed various ACC systems, including hard-coded[123], language-driven[123], [124], object-oriented [125], [126], logic-based[127], and semantic and ontology-based methods[128], [129], to address issues and improve efficiency and accuracy of compliance checking.

Although there have been promising outcomes, most of the current ACC systems are limited to verifying quantitative or objective criteria, such as numerical requirements or specified features [130]. A limited number of publications have provided insight into the presence of ambiguity and subjectivity in the field of building requirements. Research has concentrated on comprehending the subjectivity and ambiguity of constructing

requirements by offering a classification or taxonomy. Additional studies have suggested potential remedies for addressing the issues of ambiguity and subjectivity while constructing standards.

For instance, Soliman Junior et al. [131] presented several instances of subjective norms pertaining to spatial relationships. They proposed a solution based on semantic enrichment to tackle the subjective adjacency and confinement rules, but they did not offer any validation or specifics. Zhang et al [132][132] explored the ambiguity in building regulations. It categorizes ambiguities into intentional and unintentional types and identifies their origins, providing insights for drafting clearer, aiming to improve ACC systems.

Beach et al. [133] explored the integration of automated compliance checks within the construction sector, noting their slow adoption despite advances in technology such as BIM and asset information models (AIM). They investigated the gap between automation's potential for efficiency gains and its limited industry adoption. They highlighted the immaturity of planning-stage data sets and the fragmented development of compliance processes as key political, technical, and commercial barriers. While industry feedback views automation as both feasible and desirable, it necessitates human oversight. The research creates a strategic roadmap to mitigate these obstacles, aiming to industrialize automated compliance checking by 2025.

This future vision involves digitizing regulations and partly automating the compliance process to enhance efficiency while retaining crucial human control. Political and commercial challenges include a lack of government support, high implementation costs,

market readiness, and the need for cultural adaptation within the industry. The paper argues that overcoming these challenges will require collaborative efforts across all sectors to create a supportive adoption ecosystem.

Examining worldwide digitalization trends, including the use of BIM, Al Nama et al [134] explored both global projects and local efforts, such as Bahrain's "Benayat" portal, aimed at automating the process of issuing construction permits and conducting compliance inspections. Existing ACC systems face technological limitations, as they struggle to process complex building code requirements. Adoption and integration challenges persist due to manual processes, human error, regulatory and standardization issues, and the absence of machine-readable building codes. Stakeholders need training and awareness to embrace new technologies like BIM and ACC. They proposed a roadmap for Bahrain, involving legal reforms, technological adoption, and training to transition to a fully automated system for improved code compliance within the AEC industry.

In rule perspective research for developing ACC systems, Zhang[135] identified three key themes: rule classification, rule organization, and rule representation. Rule classification groups rules based on semantics and dependency, making them easier to understand. Rule organization focuses on the arrangement and interrelationships among rules, enhancing the system's ability to navigate complex regulatory frameworks. Rule representation converts regulations into computer-processable formats, maintaining their semantic integrity and accurately assessing compliance. These themes aim to transform textual regulations into automated systems for building design evaluation.

Current ACC tools often have limited capabilities and require more advanced methods to manage complex rules. These include the complexity and iterative nature of infrastructure planning, the time-consuming and error-prone manual compliance checks, and the difficulty of translating complex, dynamic regulations into machine-readable formats[136]. Additionally, the interconnected nature of regulations and the need for comprehensive data integration across different regions complicate the automation process.

The development of these tools to solve their challenges requires machine-readable regulations, comprehensive data management, and the ability to manage different regulatory versions and updates. It must distinguish between mandatory and non-mandatory rules, recognize different technical standards and issuing bodies, and account for country- and region-specific regulations. It should classify regulations by technical subject and project lifecycle stage, manage references between regulations, and support cross-modal planning for multiple transport modes. ACC tools need to address different design tasks, model relevant regulation aspects, classify rules by complexity, and recognize various regulation types. Integration with BIM and a user-friendly interface are essential to enhancing compliance checks and accessibility for engineers and planners [137].

2.4 Conclusion of this chapter

This chapter has explored literature reviews of the advancements of BIM for building compliance. The area of this work was within the 2020–2024 timeline and has successfully noted the major technological and methodological advancements with the potential of impacting the landscape of building compliance. It is evident that an automated checking system, integrated through BIM, could significantly enhance efficiency and precision in compliance processes by eliminating manual checking methods that easily get flawed.

Technological improvements in BIM, such as AI, semantic web, and machine learning, have further fine-tuned its capabilities, making it even more precise in automated rule checking. An apt example is the development of I-SNACC, a framework that relies on natural language processing in rule generation and is indicative of a move toward sophisticated yet reliable compliance.

Identified in the study are some enduring challenges, like the need for further improvements in software interoperability, the processing of complex building codes, and training and readiness of the personnel in the industry. Adoption within the construction industry itself is high culturally and technologically, which will become a major impedance to full-scale adoption of these technologies.

Future research should focus on the way to overcome these barriers and enhance the interoperability of BIM tools with improved user interfaces for mass adoption. The area calls for collaboration of the closest kind among all the industries of interest and between policymakers and technology developers in moving forward to provide an enabling environment that will enable mass use of this new integrated approach in mainstream construction practice.

Indeed, there is much progress toward the automation of building compliance with BIM, the application of this technology in full potential to construction demands continuous exertion in the development of this technology, research, and industry collaboration.

CHAPTER 3

THE PROPOSED FRAMEWORK

The timely issuance of building construction permits has necessitated the use of diverse methodologies that utilize automated code compliance verification. A variety of techniques exist, such as those based on logic (e.g., decision tables), language (e.g., markup language), and ontology (e.g., propositional, and predicate logic). Typically, existing methods prioritize making rules and their contents machine-understandable over human-machine communication [137]. This approach often fails communication with users, such as planners, engineers, and constructors, as noted in references [122], [138], resulting in significant gaps between user feedback and the developers of these techniques.

The research presented in this thesis adopts the Design Science Research (DSR) methodology to overcome the previously mentioned obstacles. This approach is suitable because it aims to address real-world issues in the industry, emphasizing the interaction among different stakeholders. The DSR is a paradigm for solving problems and has its roots in engineering and the natural and applied sciences [139]. The primary objective of DSR is to expand human understanding by developing novel creations and generating design knowledge through inventive approaches to practical challenges [140].

DSR methodology includes five stages: problem awareness, development, suggestion, evaluation, and conclusion [141]. This thesis introduces the concept of problem awareness and suggestion as a robust basis for the development of a rule representation method. The

proposal for a method of representation is grounded in abductive reasoning. The process entails the researcher choosing the "optimal" option according to a set of practical criteria.

3.1 Existing Method used by building authorities for permits.

Depending on the level of automation and technological development, Saudi Arabia's municipal authorities' permitting systems have gone through several levels as illustrated in Figure 13 . Implementing all aspects of one level before moving on is optional. Level 1 includes traditional paper-based permitting methods and reviewing drawings by hand with no automation. Level 2 includes basic e-permitting features, such as digital submission of two-dimensional (2D) drawings and simple workflows. Level 3 lets you submit digital models and can include different levels of processing automation.

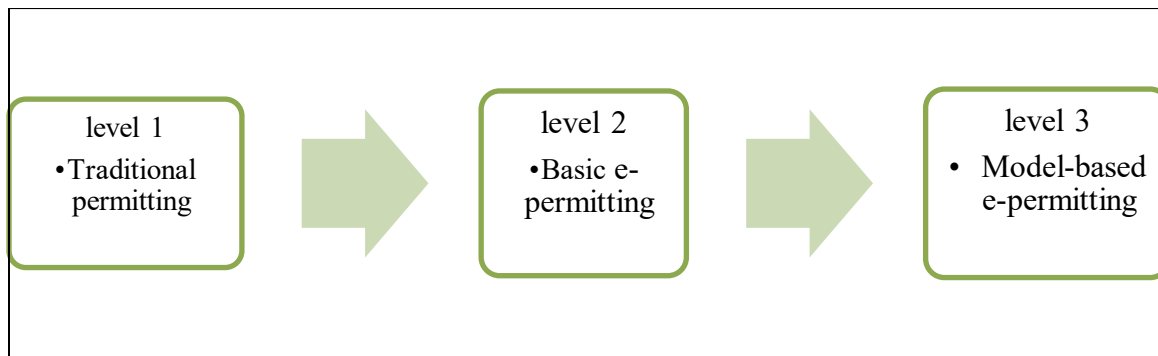


Figure 13 Categories of permitting systems in Saudi Arabia

The process of issuing permits in Saudi Arabia goes through several steps determined by the Saudi Building Residential Code (SBC 1101-CR), which outlines comprehensive guidelines for ensuring public safety and welfare in the construction industry [142], Figure 14.

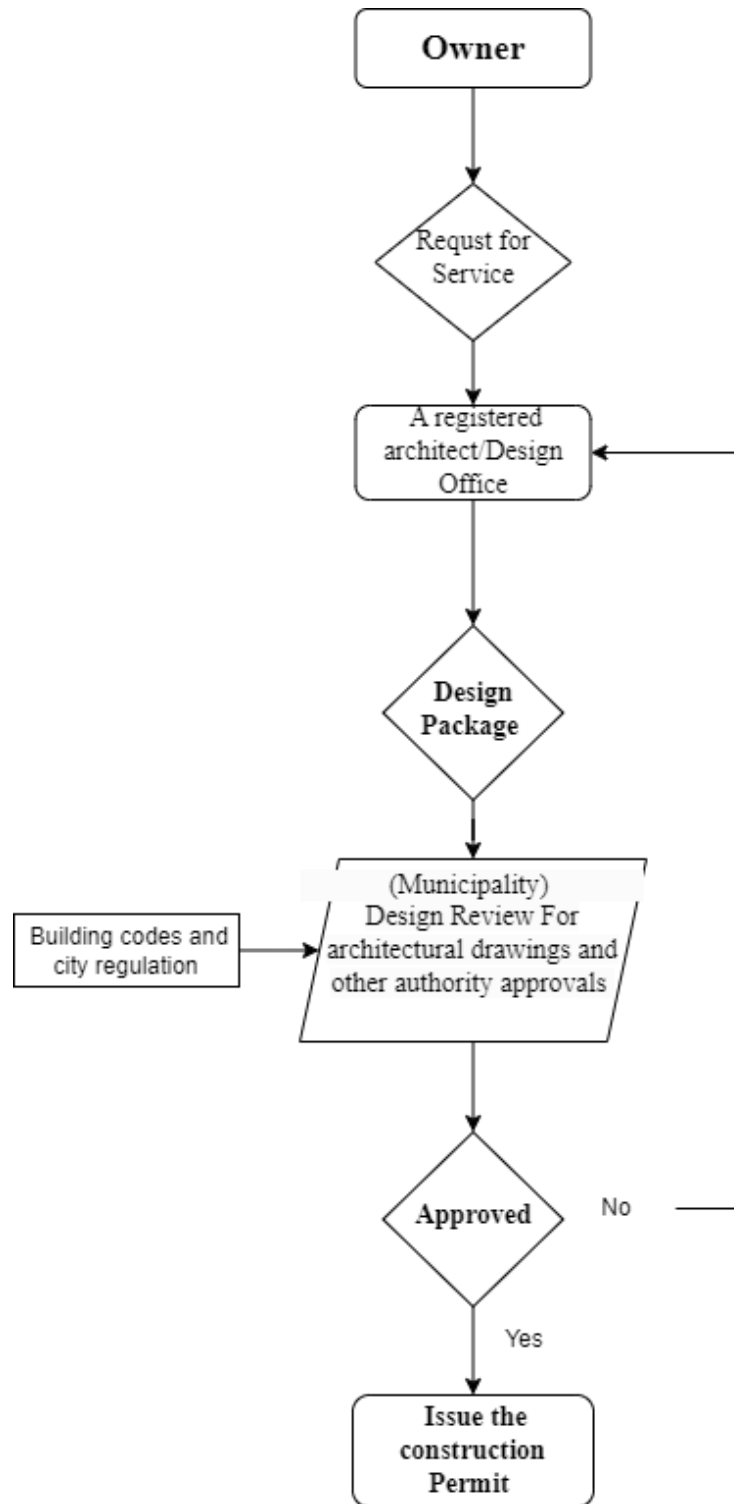


Figure 14 Building Permit Process in Saudi Arabia

To ensure compliance, the Ministry of Municipalities and Rural Affairs (MOMRA) enforces codes through the Department of Building Safety. SBC mandates permit for any construction activity, including building, alteration, or demolition. The building officials only issue these permits after reviewing and approving construction documents, which ensure adherence to code standards. They conduct regular inspections throughout construction to verify compliance with approved plans and safety regulations.

3.2 Methodology of Implementing Automated Code Compliance

Framework

The literature review identified several solutions for creating rules and evaluated certain rules to see if they could aid in identifying BIM needs. Many researchers have been drawn to automated code checking due to its focus on digital rule representation and rule-checking system architecture. This section discusses the relevant aspects of developing an ACC framework in the context of streamline construction permits. It presented a procedure and system for using BIM approaches, focusing on automated code compliance checking against Saudi local codes in the architectural aspect of residential buildings (i.e., single-family homes or villas). VPL has been used to effectively depict information through a white-box approach and full system accessibility. The proposed framework allows users to modify any aspect of the system, rectify errors, update rules, and personalize them to suit their individual needs, resulting in a trustworthy and comprehensive approach.

The framework serves as a system for interpreting and applying regulatory guidelines to design documents, ensuring that construction projects adhere to necessary standards efficiently and accurately Figure 15. The framework begins with key inputs: the Saudi

Building Code, which defines the regulatory framework, and design documents (BIM), which provide detailed architectural and engineering plans. These inputs are guided by control elements, including code and model guidelines, that ensure the rules and standards are clearly interpreted and applied consistently.

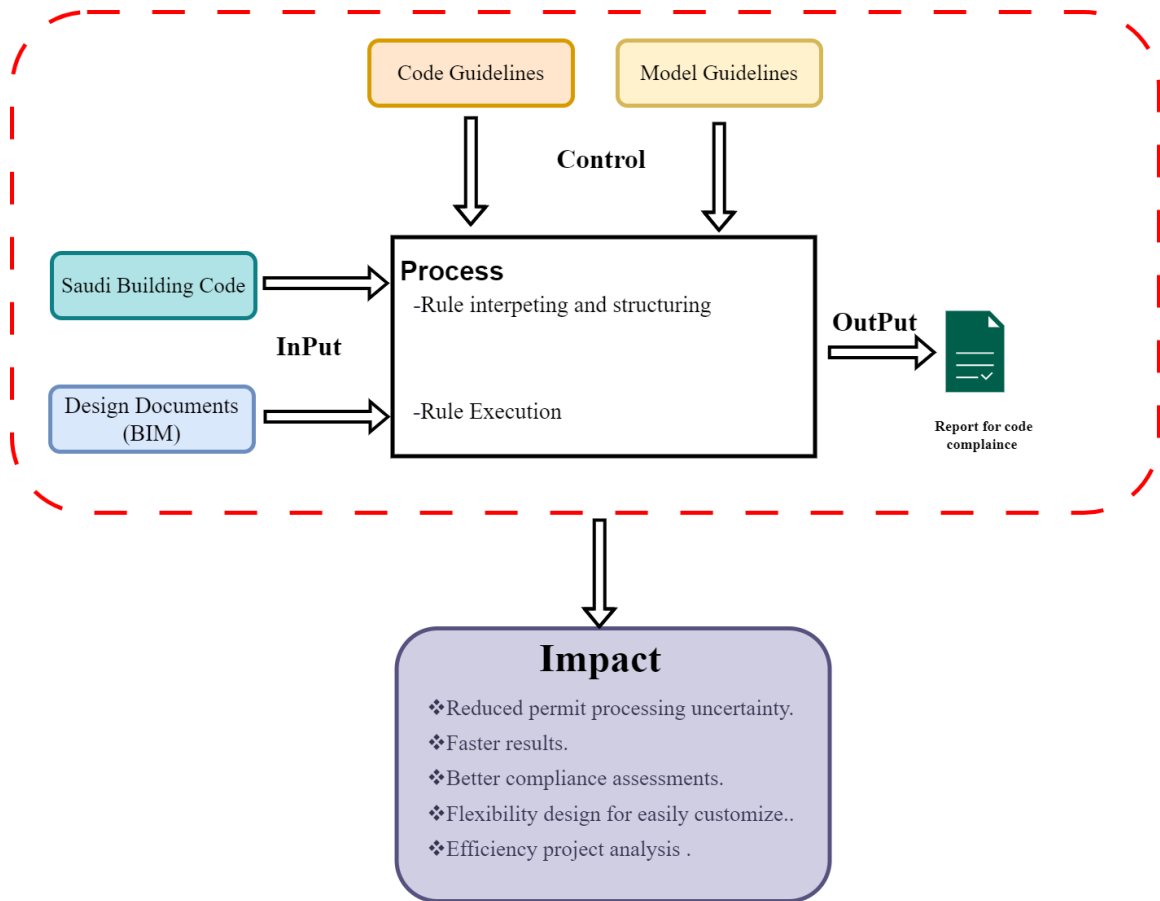


Figure 15 The proposed framework for ACC

The process includes two stages: rule interpretation and structuring and rule execution. This sequence ensures that the rules are applied systematically to the design documents, leading to the generation of a comprehensive compliance report. The following subsections describe the steps of developing, applying, and evaluating the proposed framework:

- Preliminary investigation and data collection.
- Interpreting rules.

- Identification of BIM properties (model requirements).
- Testing rule execution and Practical application
- Validation and reporting

We will refer to the BIM-based application as BIM Saudi Building Code Tool, or BIM SBC Tool. The following section describes the capabilities of the system, which led to including multiple criteria to automate the evaluation process in the BIM platform to host the BIM SBC Tool and facilitate its development. The research approach consists of the five primary components of automated code verification as illustrated in Figure 16.

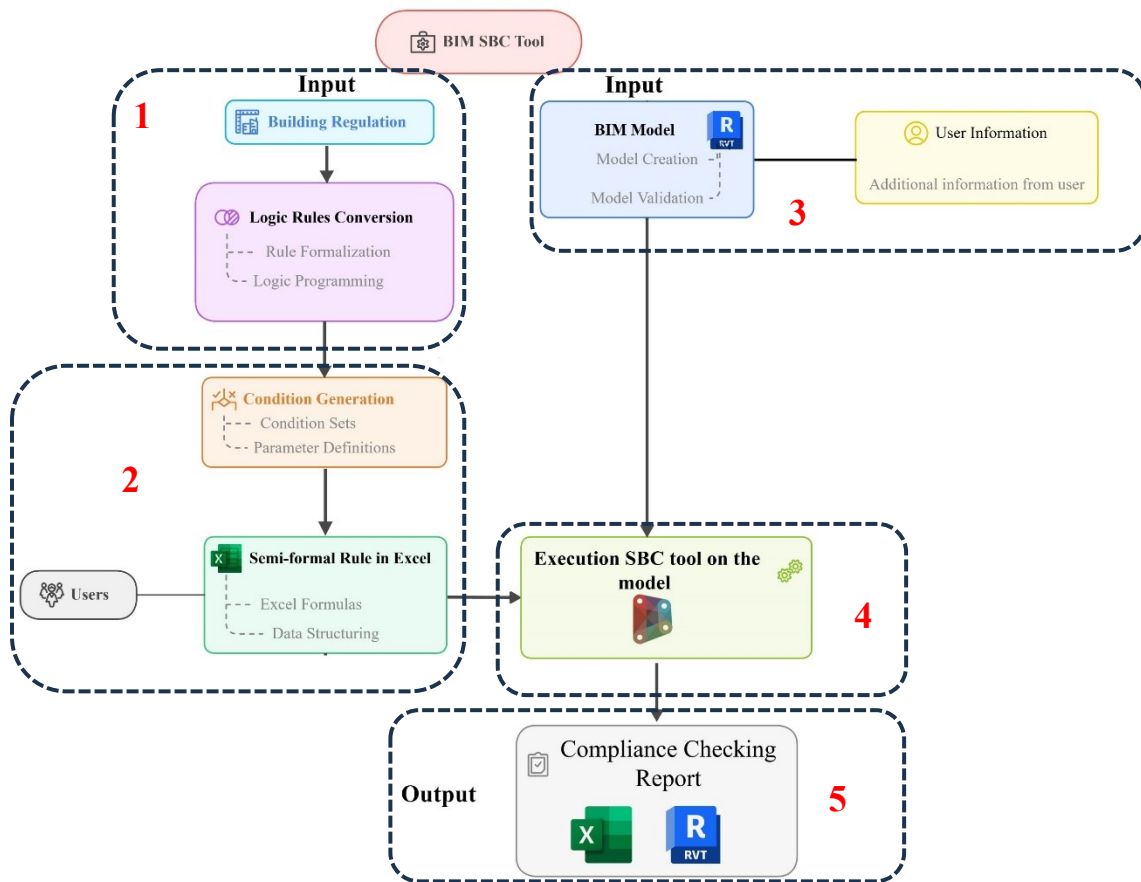


Figure 16 Method for BIM SBC Tool development.

3.2.1 Preliminary Investigation and Data Collection

The task involves understanding the building codes and regulations in Saudi Arabia by examining the legal language, extracting technical specifications, and identifying all relevant inputs. Thus, understanding and evaluating SBC is essential for collecting the system's input attributes and developing the ACC tool. Initially, we investigated the latest provisions of the Saudi Building Code to identify the constituents of the regulatory sentences. We employed the semantic markup RASE, which signifies requirement (R), application (A), selection (S), and exceptions (E), before tackling the informative clauses.

More than 556 pages have been examined to identify non-qualitative rules. We also excluded sentences from the research pool that necessitated a final assessment by human resources. Secondly, we classified the compositional units according to their syntactic and semantic attributes. The predominant modal verb in the code, "shall," denotes necessity or prohibition in the building's design. For example, by-law section 304, Figure 17, employs the modal verb "shall" to delineate the stipulations for minimum room dimensions. Other clauses commonly use "will," but informative clauses often use "may" to suggest design choices. The term "no" may also signify prohibitions within the regulations. Many sentences have multiple subjects because of their complex construction.

SECTION 304—MINIMUM ROOM AREAS 304.1 Minimum area. Habitable rooms shall have a floor area of not less than 6.5 m². Exception: Kitchens. 304.2 Minimum dimensions. Habitable rooms shall be not less than 2100 mm in any horizontal dimension. Exception: Kitchens. 304.3 Height effect on room area. Portions of a room with a sloping ceiling measuring less than 1500 mm or a furred ceiling measuring less than 2100 mm from the finished floor to the finished ceiling shall not be considered as contributing to the minimum required habitable area for that room.
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Figure 17 Restructured clause under section 304.

Thirdly, we examined the interrelations among the constituent units to enhance grouping and symbol classification. Fourth, we validated the integrity categories and interrelationships of the constituent units (visual symbols) using VPL of the established Saudi Building Code. This research focuses on examining approximately thirty rules as a target pool, classifying them into six categories, and connecting them to the semantic data pool. The structure can produce different types of building code, depending on the generator's rule-checking intent.

3.2.2 Interpreting rules

The BIM SBC Tool designed to interpret building codes and regulations by converting them into computer-readable scripts. This process relies on BIM logic, a rule-based mechanism, to transform human-readable documents into structured code. To achieve this, the authors analyze building code documents extensively, identifying key regulatory phrases, terms, and requirements. The grammatical structure of sentences examined to understand relationships between components, such as nouns, verbs, and adjectives, focusing on comparative terms like "minimum" and "greater than."

To ensure consistency and clarity, the tool detects patterns in regulatory frameworks by comparing identical statements and extracting relevant information. The tool then organizes this data into structured formats like tables or lists, capturing all essential details about building components, requirements, conditions, and comparisons, and saves them in a single Excel file. This process yields a computer-readable script that complies with building regulations, accessible from an Excel file. This script is compatible with Dynamo, a software tool capable of processing the data manually or semi-automatically.

3.2.3 Identification of BIM Properties (Model Requirements)

After defining the assessment process and extracting the input, a functional digital prototype of the project is created using suitable tools. All necessary information and properties must be included for automated compliance checking. Autodesk Revit was selected as a platform for the creation and testing of the ACC tool, as it offers an engine capable of creating personalized interfaces, a goal of this project. The software's prominence in the Middle East region and its multidisciplinary nature, along with compatibility with other software tools and ease of learning, played a significant role in the decision.

In Revit, project template files (*.rte files) contain various elements, such as view templates, loaded families, defined settings (units, fill patterns, line styles, view scales, etc.), and geometry. Often, the designer of relevant submodules must manually input these attributes. In some cases, it may be possible to identify specific properties (width, height, etc.) directly from the geometric model. Whenever possible, properties should be automatically derived to minimize the risk of inaccurate data due to manual entries. We will use all the specified data for the assessment, and a set of modeling guidelines will be

followed. The case study will be used to assess the BIM SBC tool, which will provide expedited results for validation.

3.2.4 Testing Rule Execution and Practical Application

The implementation of the code-checking system depends on selecting the software that best meets the user's needs. Often, the establishment of initial requirements is overlooked, but this is crucial for the effectiveness of the verification process. The assessment will be incomplete and prone to inaccuracies if performed on a model that lacks sufficient data. Additionally, regulatory restrictions would only examine part of the data, making excessive data accumulation inefficient. Inadequate preparation of the system may also lead to the failure of the verification procedure. Therefore, it is essential to define the project requirements and the intended application of the system from the outset to prevent errors and avoid unnecessary delays.

The Dynamo engine was chosen as the platform for the implementation and testing of the ACC tool, as it integrates with Autodesk Revit interfaces. Moreover, the system integrates the necessary assessment data from the BIM model and local standards, enabling the user to perform the assessment calculations and display building compliance. In this phase, the BIM SBC Tool developed, establishing a set of new shared parameters based on the SBC assessment requirements. Finally, the Dynamo script is used to assess the requirements and generate a compliance report that identifies the properly complied requirements and determines the project's approval status. This section demonstrates how the system

processes input, interacts with users, and generates the final compliance report. The inputs comprise building codes and BIM Revit-based architectural design models. A three-step approach presented to achieve optimal results, as outlined below:

- i. Determine system functionalities and establish the environment:

Once the BIM model has all the necessary properties, we can execute the defined rules. The authors will use Dynamo to program all the established rules from the interpretation phase and the identified research procedure. Dynamo is a visual programming tool within Revit, utilized to create a proof-of-concept prototype. The verification procedure and compliance outcomes might subsequently be executed directly in Revit. During this phase, we develop the BIM SBC Tool application using Dynamo scripts, then apply them to hypothetical and real-life case studies to highlight their practical application and align with the code requirements. Furthermore, we designed the scripts to function in a variety of scenarios and with varying levels of complexity in BIM models. The scripts gather the required assessment data from the BIM model, allowing the user to perform the assessment calculations and display the building model.

We conducted a thorough analysis and dismantled each action and process necessary for model checking, resulting in a group of node elements that determined the system functionalities as shown in Figure 18:

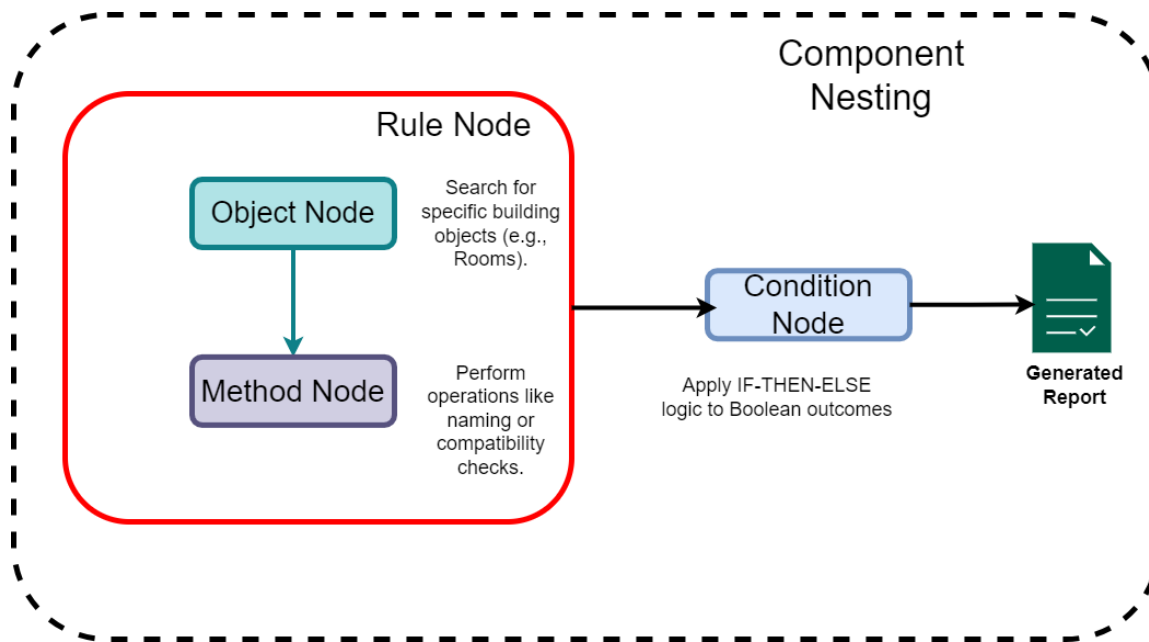


Figure 18 Node type for visual language in building model checking.

1. Object Node

The object node specifically searches for a building object with defined properties, which it indicates by nesting. If the object node assigns no nesting, it queries all objects in the building model. It may encompass numerous characteristics. For instance, if the “Room” object node contains no properties, it queries all “Room” objects within the building model. However, if there are properties, such as a room named "bedroom," this node queries the "bedroom" in the model.

2. Method node

It conducts a certain, assigned function on the input object node. The database comprehensively defines the functions of each technique. Each method node possesses various function types, resulting in a varying number of input ports across nodes. The "room name" approach requires the identification of an object by its name. Nevertheless, the available method" requires the interaction of two entities to determine their

compatibility. The input port of the method node, along with the object node and the output port of the node, must contain Boolean values. Consequently, we can link this node to the rule node, identifying it as the rule node's name.

3. Rule Node

The rule node must comprise at least one object node and one method node. The rule node nests all visual elements that indicate the rule. The rule node possesses a simplistic design and displays the rule name within a rectangular node. One can represent a rule node as a singular entity, but it also could expand its nesting to include all associated components. This enables the user to regulate the degree of detail in the visual language correctly. The rule node's input value sums up to a Boolean variable, which can produce either true or false outcomes. The output, a Boolean value, signifies the rule node's ability to reconnect to itself and integrate any other type of node to produce Boolean rules and outcomes.

4. Condition node

It explores the relationship among Boolean values. As a result, you can link this node to the rule node's output port, the method node, or even to itself. This node establishes IF THEN, and ELSE relationships among Boolean values to delineate conditional and key statements, providing a Boolean value as an output port. If the rule node associated with the IF input port is true, then the rule linked to the THEN input port must be evaluated and satisfied for all rules to be deemed successful.

5. Component connection

It is a connection that ties the output port to the input port of the nodes. This connection is essential for linking all nodes and transmitting the included information. We can create "and" and "or" relationships as logical operators, particularly for the transmission of Boolean results. The right-to-left data flow defines the logical relationship among Boolean outcomes.

6. Component nesting

It significantly enhances the intuitiveness of the visual language. Clarifying and delineating all incorporated nodes within a project constitutes a textual representation, underscoring the significance of context and regulatory flow. This nesting, which consists of specific nodes such as a rule node and an object node, encapsulates detailed information and helps the user manage the representation level by expanding and contracting the nesting. Gathering the nesting may obscure excessive detailed information, while increasing the nesting facilitates verification.

ii. Create a module for verifying models.

The model verification module checks the building design model for compliance with building codes and finds any missing information. It transforms models into invariant signatures. Building codes can use invariant signatures to conserve elements and locational information from the input BIM model. Wu and Zhang's [28] methodology is the basis of the model validation procedure. The model validation module has discovered four separate categories of target building code concepts: first, concepts that can be directly generated from BIMs called explicit concepts; second, concepts that can be inferred from the model's explicit information in a consistent way; third, concepts that need user judgement and

assistance; and lastly, there are concepts that represent system defaults and do not represent actual objects from a building's design.

Explicit concepts are simple. For instance, we can directly create an instance of a wall idea with any relevant attributes, such as length, by using a wall object from Revit, such as one that is depicted as a wall standard. For inferable concepts, use heuristic principles to deduce the desired information for inferable concepts like the ratio of land to building area. The procedure defines target concepts and transforms corresponding information into logical realities, embodying building design models. This module accepts logical rules that denote building code requirements and BIM instance models that signify building design. It generates logical facts that are prepared for validation against the logical rules, thereby improving code verification.

iii. Develop and check execute rules of the module.

The execution module receives three types of input: logic rules, logic facts, and activation conditions. These allow it to conduct the checks and identify instances of non-compliance. At this stage, the system can detect instances of compliance and non-compliance automatically. The activation conditions are the first steps in the execution. Based on the prerequisites stored, the activation conditions filter and choose logic facts for target ideas. We remove the logic facts that do not meet the prerequisites to prevent false-positive examples of non-compliance. Once the preconditions are satisfied, we examine the logical facts that align with those rules. We apply logic rules to each filtered entity in the logic facts to identify instances of non-compliance. So, the system framework can verify that design facts are compliant at the instance level; that is, it can identify any potential cases

of non-compliance associated with each instance of a target building code idea. For the target concept "levels," we detect and check every level of the input building design model against rules related to egresses. We generate a list for each rule, storing the compliance and non-compliance cases, to represent the checking result. The execution module receives the logic rules, logic facts, and activation conditions as inputs and produces lists of compliance checking results. A list associates each rule, and an element in that list represents each instance of a target concept.

3.2.5 Validation and reporting

The Dynamo script will be run to evaluate understudy indicators, and a compliance report will be generated, indicating which criteria are being sufficiently complied with and whether the project approved or not. The BIM SBC Tool Rule Report comprises the analysis output of the building evaluation. The application itself will display the “rule report” by presenting the individual score of each criterion as well as the building global score, and it will be as follows:

1-Module for generating compliance checking reports:

The results of the compliance check will be reported when the logic facts have been processed by applying the logic rules compliance reporting module. The system reporting module will choose the reporting format and content, and since the logic reasoning process directly generates lists of compliance and non-compliance cases, the system must transform these lists into human-readable outputs. We do not expect the end users to have a background in logic programming or be able to

interpret logic clauses; we link the results with the corresponding building code requirements in the original text (instead of logic rules) to achieve that.

The report-generating module's overarching objective is to make it simple for customers who are not familiar with logic programming or computer programming to view and comprehend the initial specifications and outcomes related to the building code. The Autodesk Revit environment will receive this output directly, serving as a real-time decision support tool, while an Excel spreadsheet will conduct the comprehensive and final evaluation of the tool.

2- Iterative improvement and system testing

To assess the usability of the system, we should evaluate each function and their interrelationships to confirm the practicality of the proposed framework. For example, when a building design model modified within the system, subsequent modules, such as the model validation module, should automatically update to reflect changes. It is crucial to examine both the independence of functions and their interconnections. Since the processing of building codes and building design models occur separately, the framework should allow users to adjust logic facts and modify building code inputs independently, even when the building design models processed later. After this phase, the framework corrects any errors found in the training models due to human mistakes during compilation, activation conditions, or flawed logic facts resulting from input errors.

CHAPTER 4

IMPLEMENTATION OF THE PROPOSED

FRAMEWORK

This section describes the implementation of a framework that includes inputs, such as the building code and building design model. The process involves interpreting and executing the rules, followed by outputting reports on building code compliance. It illustrates a structured approach to automated building code compliance checking using a BIM-based tool (BIM SBC Tool).

The procedure begins with "Input Data Collection," which gathers significant building code requirements and transforms them into machine-readable representations. The subsequent "Analysis and Compliance Checking" phases use these inputs to perform automated verifications based on established logical principles. Each step of the procedure data input, analysis, and reporting—facilitates effective and automated compliance verification to ensure adherence to the Saudi Building Code (SBC). The system demonstrated exceptional efficiency in dynamically processing multiple rules, leading to enhanced speed and accuracy compared to conventional manual checks.

4.1 Case studies

Two case studies were conducted for experimental testing to ensure framework reliability. The first case is verification case study to ensure the framework could accurately analyze

compliance in a simulated environment. It was designed by the authors to serve as the final model for verification purposes. The second one the verification case study a design office located in Riyadh, Saudi Arabia, provided the plans and specification to test the framework ability to handle real-world complexities and deliver meaningful results. We developed each case in Revit platform. All models represent fully functional, comprehensive buildings, complete with several rooms, walls, doors, and additional architectural elements.

4.1.1 Case studies description

The verification case study is a two-level residential building that embodies the most representative characteristics of Saudi villas Figure 19. It is a detached single-family house with a colonial ceramic tile roof and ceramic brick masonry walls. The house includes a Mulhaq (ground annex), a guest hall, a living room, multiple cold and hot kitchens, a family yard, a side yard, a driver's room, a maid's room, three bedrooms, one master bedroom, eight bathrooms, a gaming room, an office, and parking. The construction is located on a plot of 351 m² and has a gross construction area of 230 m². Figure 19 illustrates the distances between the building and its property limits, showing a 6.00 m front offset, a 2.00 m back offset, and lateral offsets ranging from 3.80 m to 2.25 m. The ceiling height in interior areas ranges from 2.70 m to 3.00 m. The total building height is 13.30 m. To access the building, there are two different entrances, one for vehicles (parking) and another for pedestrians.



Figure 19 Verification Case study

The second case study examines an existing two-story family residential building in Riyadh, Saudi Arabia, spanning two levels Figure 20. The building occupies a 392 m² site

and has a total gross construction area of 203 m². The house features a men's guest hall, a women's guest hall, two living rooms, a kitchen, a dining room, a driver's room, a maid's room, three bedrooms, one master bedroom, six bathrooms, an office, and parking.

In terms of building implementation, the property includes a 5 m front offset, a 3 m back offset, and lateral offsets ranging from 3.40 m to 2 m. The ceiling height in interior areas varies between 2.70 m and 3.00 m, with the total building height reaching 12 m. Access to the building is provided through two separate entrances: one for vehicles (parking) and another for pedestrians.

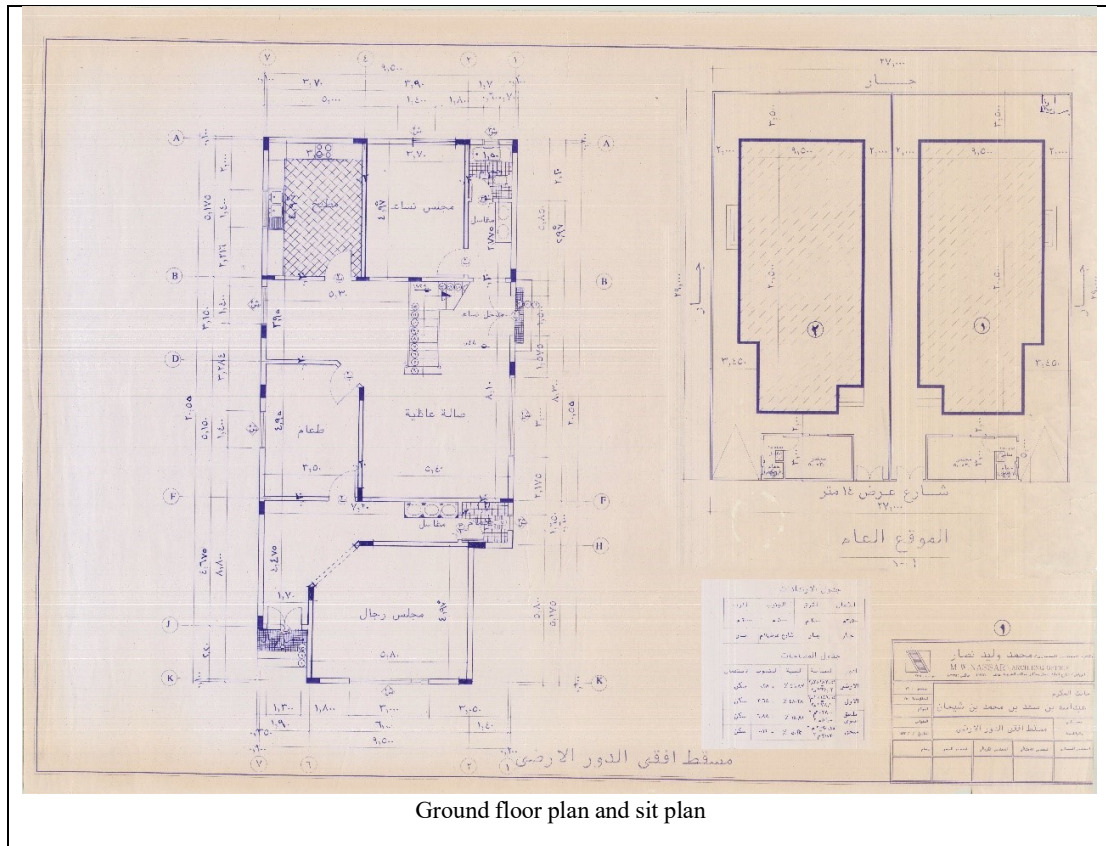




Figure 20 Validation Case study

4.1.2 Guidelines for modeling case studies

To ensure that case studies provide appropriate data for ACC, it is necessary to establish several guidelines. Additionally, the selection of consistent semantics and the detailed delivery of required information for the use case are crucial, along with the accurate categorization of stories and the clear depiction of spaces and areas. Building information modelers primarily rely on the essential elements identified during the model inspection as guidance for implementation, while designers also benefit from supplementary recommendations.

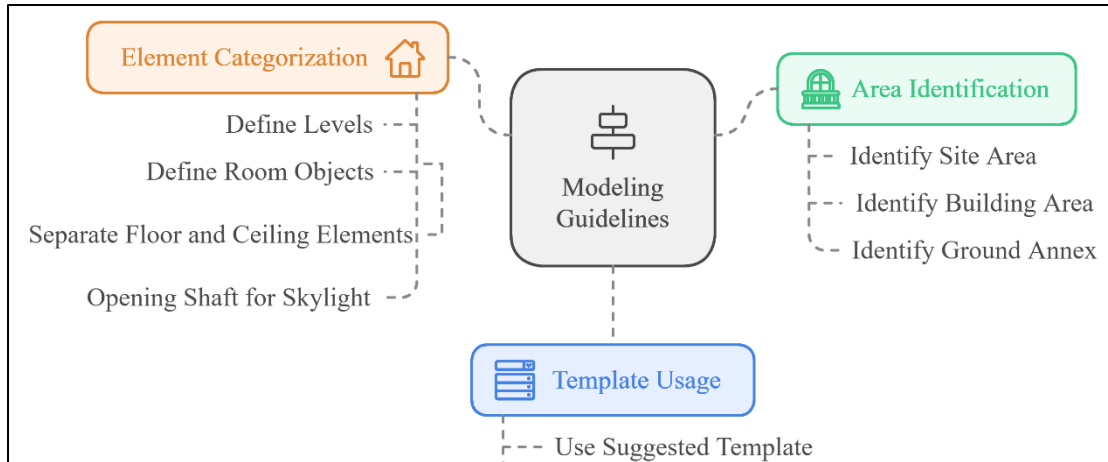


Figure 21 Modeling guidelines.

To guarantee the functionality of Dynamo script during the modeling phase, the following requirements are outlined, **Figure 21** illustrate the main guidelines:

1. Using the suggested "Template," which already contains the necessary building code parameters for analysis recommended.
2. In Autodesk Revit, go to the Architecture tab and find the "area plan" feature. Here, the user must identify the site area, the building area, and the ground annex.
3. The "Floor" category should reflect the building's measured height. The names in the names file "Revit names" are used as an identifier for all "elements" used in the drawing.
4. All names are "case-insensitive" according to the space names table.
5. "Levels" are defined according to the names table Table 2.
6. The "Room Object" defines all spaces, including the rooms of the building and the attached building.

7. The "Room Object" defines the building entrance/building lobby, but it does not include the entrance stairs from the courtyard.
8. According to the floors and levels table, a wall cannot extend to more than one floor.
9. Any floor must link all its components to the lower level of the same floor, and the courtyard level only links to the fence elements.
10. The common elements between the fence and the ground floor annex or the silent building into three levels: the courtyard, the ground floor, and the ground floor annex level.
11. Separate the floor and ceiling elements between the ground-floor annex and the main building.
12. An opening shaft represents the skylight, which is continuous throughout its entire height and not divided by the floors.
13. The courtyard level correlates with the courtyard level.

The automation of this process was implemented within the Autodesk Revit template. The model was converted into a list containing sub-lists of information for each component, including the necessary data for the study. This data is then used to compare the features of each component with the building code standards to determine compliance with the applicable regulations.

Table 2 Floors and levels in Rivet

Story/Floor	Base Level	Top level
Basement Floor	Basement Level	Ground level
Grond Floor annex	Ground level	Ground annex roof level
Ground Floor	Ground level	Level 1(Roof level in case first level does not exist)
First Floor	Level 1	Level2
Second Floor	Level 2	Roof level
Roof Floor	Roof level	Upper Roof level

4.2 Input and Evaluation Criteria of Framework

Following the adopted framework, the first step involved collecting and extracting data from the building code. However, we chose the manual approach to manage information effectively. We often formulated regulations implicitly, employ quantitative data, and provide information that is highly specific and pertains to details. The system provides a variety of inputs for the user to establish conditions. For the script to be effective and adaptable for various users, it must include sufficient flexibility to accommodate different modeling habits, allowing the end user to adjust them via an external Excel file without requiring programming experience. Since each user possesses individual modeling standards, the user must have the capability to adjust the entry conditions in the input.

Here, users define the rules as readable values, which are typically unhidden and transparent for the user. This approach is different from most commercial applications that follow the black box method, which involves excluding the design expert from the rule

creation process and directly inserting the values of variables. The "white box" methods used in this research, like VPL, allow the user to understand the processing steps and allow for adjustments, as illustrated in Figure 22 Inputs data for the system, which is an Excel sheet that encompasses all inputs and extracted data , where various criteria names are listed according to building code and can be modified to align with current modeling techniques.

	A	B	C	D
1	Floor	Area (%)	Comments	
2	Ground Floor	70	Fraction of land Area(m^2/m^2)	
3	First Floor	75	Fraction of land Area(m^2/m^2)	
4	Second Floor	100	Fraction of Below Floor(m^2/m^2)	
5	Upper Annex	70	Fraction of Below Floor(m^2/m^2)	
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				
16				
17				
18				

Figure 22 Inputs data for the system

We classified all the clauses to determine which categories were appropriate for the processes. An analysis of the Saudi Arabian building code revealed additional regulations and standards that buildings must comply with, including minimum level heights, maximum allowable building area, and the minimum window-to-wall ratio required for adequate lighting and ventilation. Based on the analysis of classifications, we decided to classify all the regulations into six distinct categories from the data listed in Table 3 .

Table 3 BIM SBC criteria requirement

Categorize	Criterion Description (requirement)	Inputs (BIM model)
C1 (Utilization percentage of building floors)	Building Area (ground floor with annex) to Land Area	70 %
	First Floor Area to Land Area	75 %
	Second Floor Area to First Floor Area	100 %
	Roof Floor (Upper annex) to Floor Area below it	70 %
C2 (Building edge offset from land borders)	Front setback	3 m
	Side setback	1.5 m
	Upper annex	1.5 m
C3 (height of the building)	Maximum point	14m
C4 (elevation of the level)	Basement floor	(-2.2-1.3) m
	Ground floor	(.30-1.3) m
	First floor	(3.30-4.30) m
	Second floor	(6.30-7.30) m
	Roof floor (upper annex)	(9.30-10) m
	Roof upper	(12.3-14) m
C5 (Area of Spaces)	Bed room	6.5 m ²
	Sitting room	11.2 m ²
	Dining room	11.2 m ²

	Living room	11.2 m ²
	Bathroom	2.4 m ²
	Kitchen	5 m ²
	Toilet	1.5 m ²
	Guardian Room	6.5 m ²
	Maid's Room	6.5 m ²
C6 (Window to Wall ratio)	Window to Wall ratio	25%

Consequently, we anticipate a variety of input types, which we have categorized into three parts:

- BIM Model: This includes data related to the model, such as geometric and identity information, or data incorporated into the model through primarily quantitative and shared parameters.
- User Interface: Refers to qualitative information and data that users need to provide the BIM SBC Tool through a Dynamo interface, as illustrate in Figure 23.
- BIM Tools: data demanding additional tools for model simulation.

The BIM SBC Tool, built on a Dynamo-based framework, will seamlessly integrate user-provided interface data and BIM model data within the environment of Autodesk Revit.

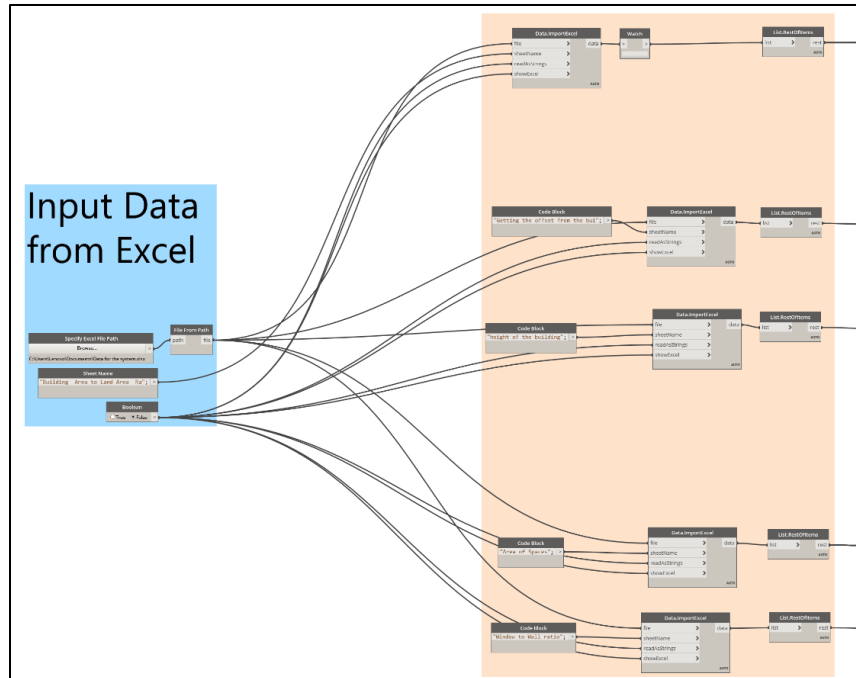


Figure 23 Dynamo user interface for the inputs.

4.3 Rule Execution and Case Study Application

The BIM SBC Tool developed using VPL in Dynamo to process and extract data from the BIM model. It automates the evaluation of essential building data for code compliance and provides a user-friendly interface for finalizing analytical outputs. Dynamo used to program calculations by analyzing the assessment procedure for each criterion within the BIM SBC Tool. The tool's functionality relies on data collected from various BIM model categories, with each criterion focusing on evaluating and filtering the relevant components within these categories. Figure 24 provides an example of the nodes for initiating the Dynamo script and illustrates the data collection process for each category. Criteria employ this strategy to gather evaluation needs, since data is fundamental to the model.

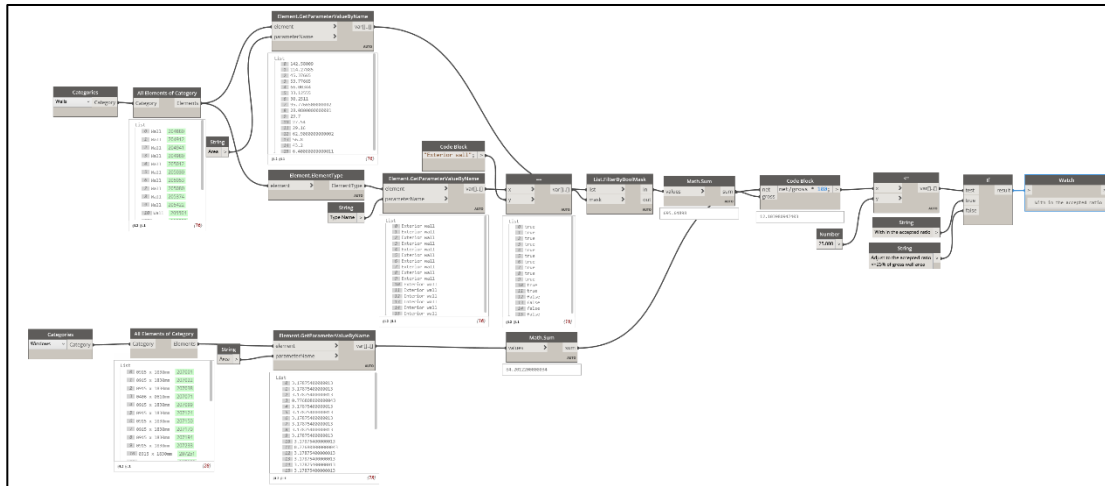


Figure 24 Data processing and collection in Dynamo.

As noted in section 3.2.4, the BIM SBC Tool requires supplementary information not included in the BIM model. To address this, we utilized Dynamo to create user interfaces that allow designers to input the necessary assessment data or modify the script as needed. When the BIM SBC Tool launched, a series of windows appeared within the Autodesk Revit environment, designed to collect local and external data for analysis. The process for this functionality depicted Figure 25. For criterion C4 (buildings levels), it requires prompted the development of specialized pop-up window. The assessment computations, normalizations, and qualitative quantification are carried out by BIM SBC Tool after the necessary data for each criterion has been collected Figure 26 shows the whole process for the research.

The first category pertains to the ratio of building area to land area, considering the occupancy rates of the ground floor and ground annex, as well as the utilization coefficient of the upper floors, which is based on the occupancy rate of the lower levels. Users require to define the site's perimeter, building area, and permeable region, as previously outlined. This data is crucial for the Dynamo process to assess all site-related indexes, making this step indispensable. A conversion node incorporated into the procedure to extract area values from the Dynamo input, which originally included the units, value, and area name (e.g., " area of building: 230 m²" simplified to "230"). Dynamo then applied the calculation methods and executed them automatically to verify the building's compliance.

The results show favorable results for case studies. For verification case building construction site displayed an occupancy rate of 68.7% (less than 70%) on the ground floor, a utilization coefficient for the first floor of 45% (less than the mandatory 75% of the land area), and an upper annex utilization rate of 51.3% (less than the mandatory 70% of the below-floor area). The validation case building construction site presented an occupancy rate of 56.5% (less than 70%) on the ground floor and a utilization coefficient for the first floor of 46.7% (less than the mandatory 75% of land area) as well as the upper annex utilization rate of 54% (less than the mandatory 70% of the below floor area).

The second category of the Dynamo script focuses on the building's offset distances from the site boundaries. We established the essential criteria for initiating the Dynamo script, using the same techniques as the prior indexes (verification case Master Plan: the front offset is 6 m, the lateral offset is 2 m, and the back offset 2 m ; validation case Study Plan: the front offset is 5 m for, the lateral offset is 1.80 m , and the back offset is 3.3 m). The Dynamo script then modified to calculate the distance between the building faces and the

user-defined site boundaries, comparing these measurements with the regulatory requirements. As illustrated in Figure 26 , both case studies successfully met the minimum required distances and approved for these indexes.

The third category focuses on analyzing the maximum building height. According to the Saudi Building Code, the maximum allowable height of 14 m used as an input for the Dynamo script. The script automatically detects the building's highest point, measures its distance from the site level, and compares it to the code requirements. The case studies approved for this category, with the verification case building measuring 13.3 m and the validation case building measuring 12.3 m.

The fourth category of the script pertains to the examination of the maximum height of level in the building along with their respective heights. As previously mentioned, a residential building in Saudi Arabia has a maximum of three levels plus an upper annex, with a maximum height of four meters and a minimum of three meters for each level. Dynamo introduces this value as an input to initiate the script. The script then encounters the number of levels in the building: specifically, three levels for verification case building and three levels for validation case building. Each level has its upper annexes and aligns with the accepted height. Dynamo automatically gathers this information from the model, resulting in a correct outcome for this index.

The fifth category in the Dynamo Script pertains to the analysis of the Saudi building code, specifically the minimum room area. We design this analysis to extract space areas from a Revit model by selecting the 'Rooms' category, retrieving all relevant elements, and comparing them with the minimum requirements of the Saudi building code, as shown in

Table 3. The Dynamo script conducts the analysis by filtering out invalid or unplaced spaces and retrieving the “Area” parameter for each room. We can also retrieve additional parameters for further processing, such as names, levels, or departments. The script processes the data by performing unit conversions (if necessary), grouping, or sorting spaces by criteria like levels or departments, and calculating totals or summaries using aggregation functions. The script then gathers information about each building room to determine its total area. We repeat this process for the remaining rooms, identifying each room's area. Finally, the building results compared against the building code requirements to assess whether the building qualifies for construction approval. The verification case building case study successfully satisfied all the criteria, while the validation case received approval for all its indexes. It is important to note that the Dynamo script links names of room to the “key names” listed in **Table 3**, requiring users to name rooms accordingly.

Window-to-wall ratio is the final index in the Dynamo script. The script performs this analysis to determine whether the window area meets the minimum requirements set by the exterior walls. It begins by retrieving wall and window elements from the Revit model. We filter the walls to only include "exterior walls" in the calculated total area of exterior walls and then compare them to the window area to determine if they fall within the accepted range. In the case studies, we successfully met all the criteria.

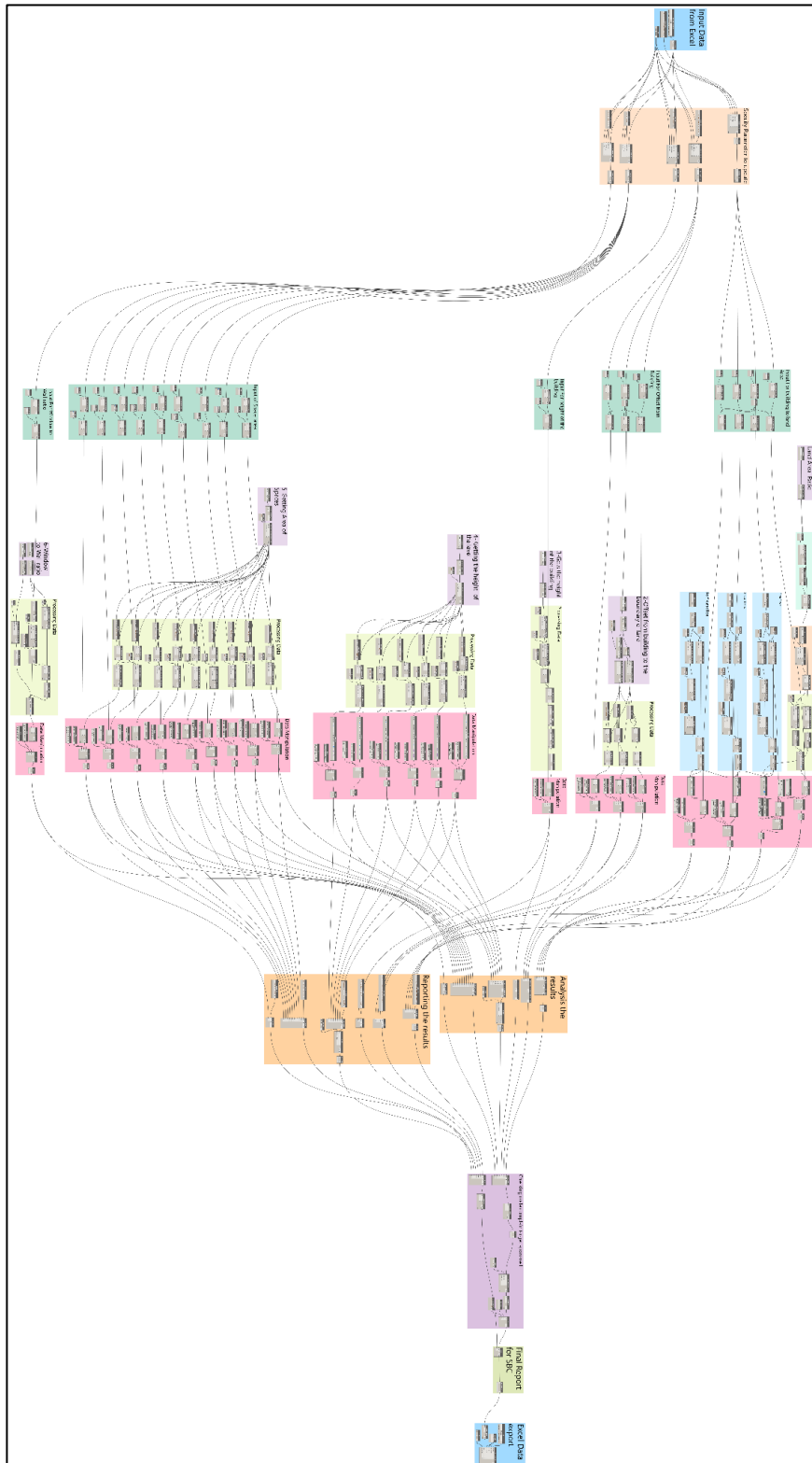


Figure 26 Dynamo user interface development for the system.

4.4 Generate Compliance Checking Report

Lastly, A module developed to generate reports displaying the results of the compliance checking process, making it the perfect case. This module utilizes the Dynamo environment to apply logic rules to logic facts, a process that bears similarity to the rule execution module Figure 27. It described the compliance checking process and included data at the beginning of each prepared report. The BIM SBC Tool shows a pop-up window in the Autodesk Revit environment that includes the building's approved design according to the Saudi building code and the specific qualitative scores of each criterion. At the same time, the BIM SBC Tool generates an Excel document that includes the overall building score and quantitative and qualitative scores for each criterion. The “output” node shows six outputs, each corresponding to the evaluated indices previously mentioned in this section: utilization coefficient, front offset, rear offset, lateral offset, maximum height, number of levels, room area, and window-to-wall area ratio. It documents the relevant information for each instance of noncompliance, enabling the system to present the illegal entity, the incorrect logical rule, and the associated building code requirement. Figure 28 illustrates a particular example of the report. Engineers will be able to quickly identify the problem areas of the building's design and implement fixes.

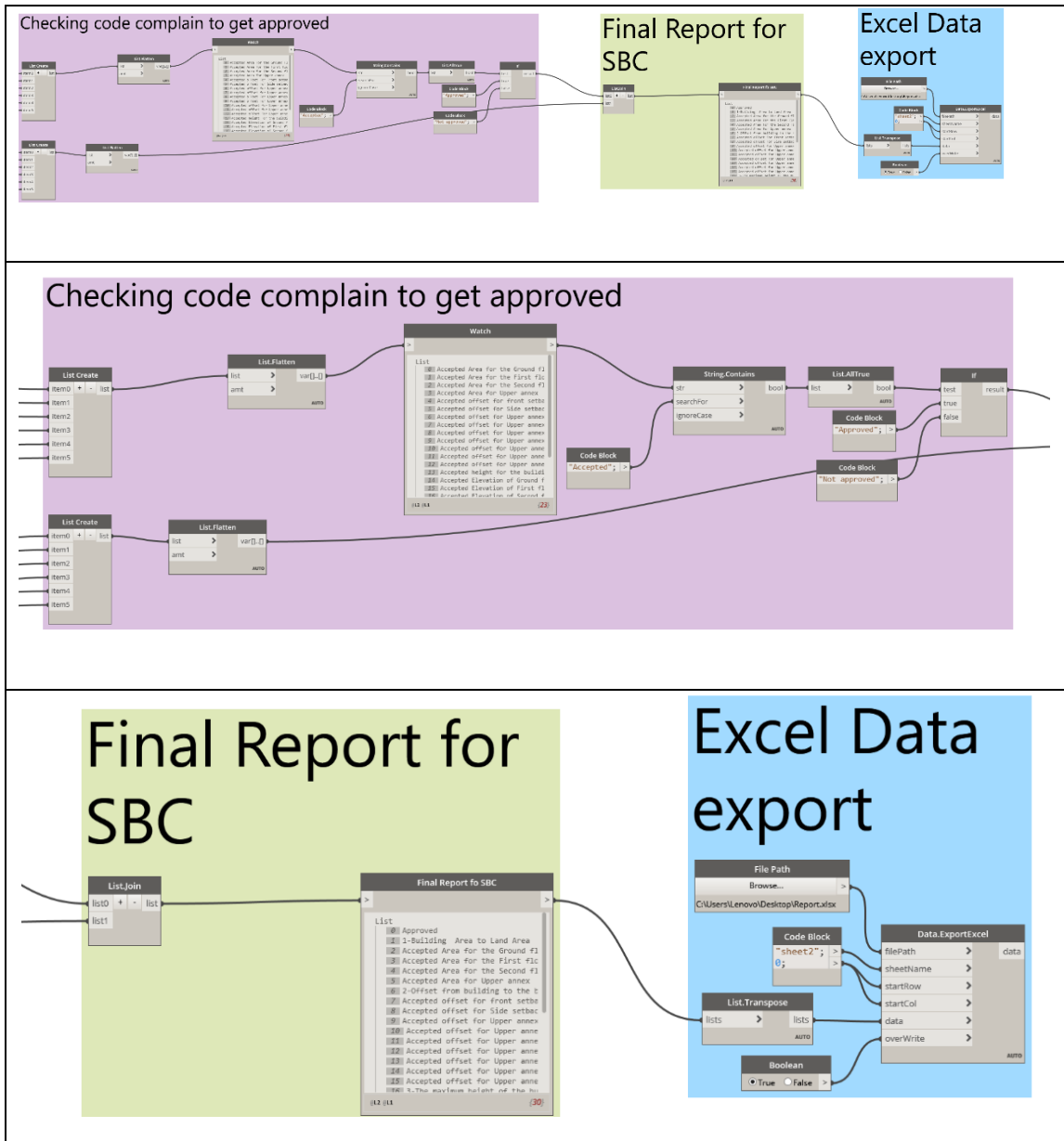


Figure 27 Building analysis results in a Dynamo environment.

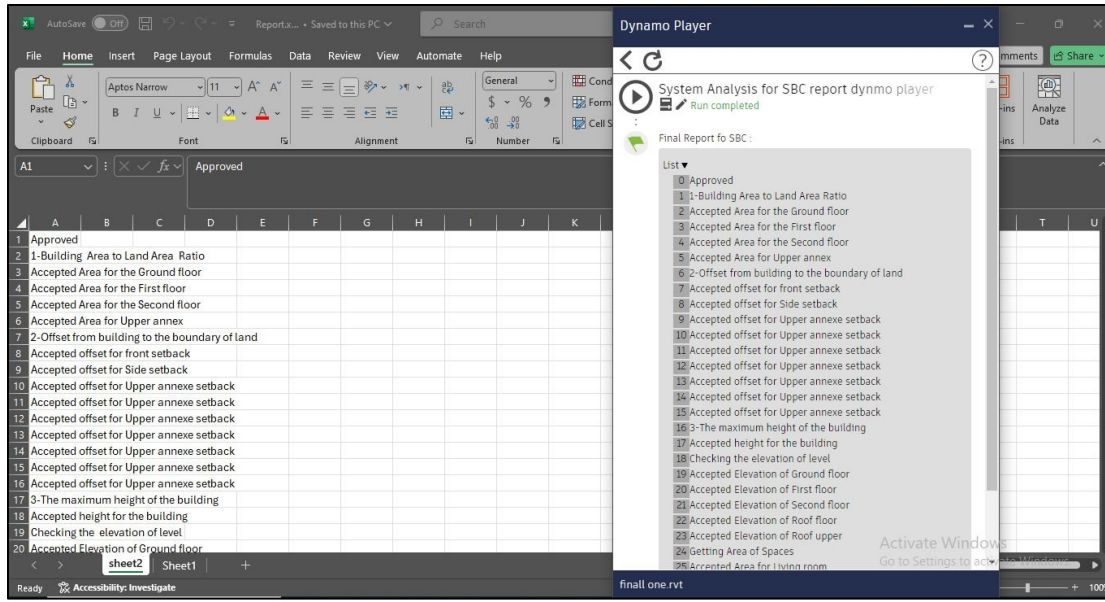


Figure 28 Output a report in Dynamo Player and Excel

4.5 Discussion

Different scenarios have been analyzed in the framework for its functionality, adaptability, and reliability in practical applications. This includes several changes to certain parameters of the BIM SBC Tool, enabling real-time modifications and dynamically verifying compliance. Each scenario aimed to explore specific aspects of the framework's functionality and its ability to address diverse regulatory requirements effectively. In the first scenario, the building area utilization ratio was modified from the standard 70% to 50% of the total land area. This adjustment tested the framework's capability to adapt to changes in input data and verify compliance based on updated criteria Figure 29. The framework successfully processed the revised input, demonstrating its flexibility to accommodate varying project requirements and provided real-time feedback to users.

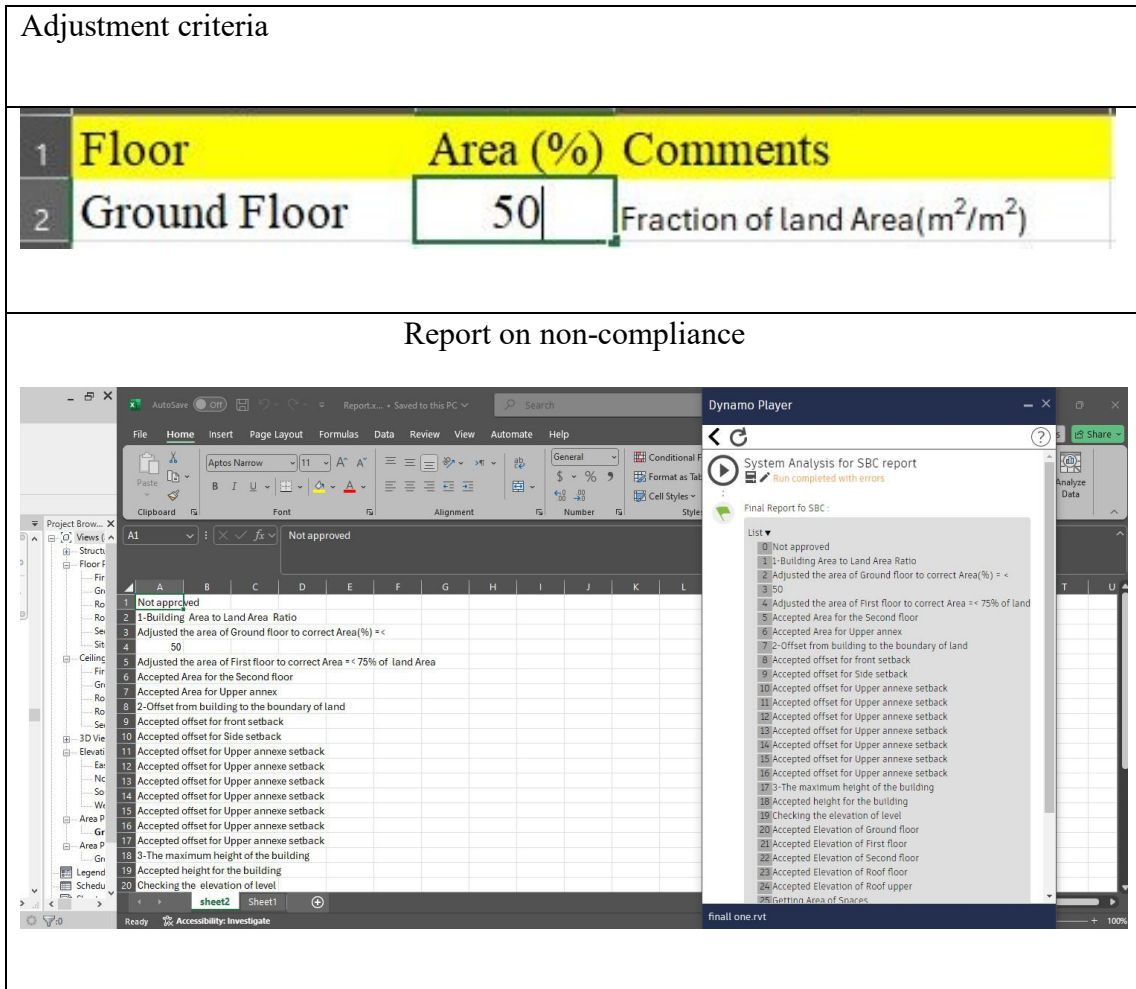


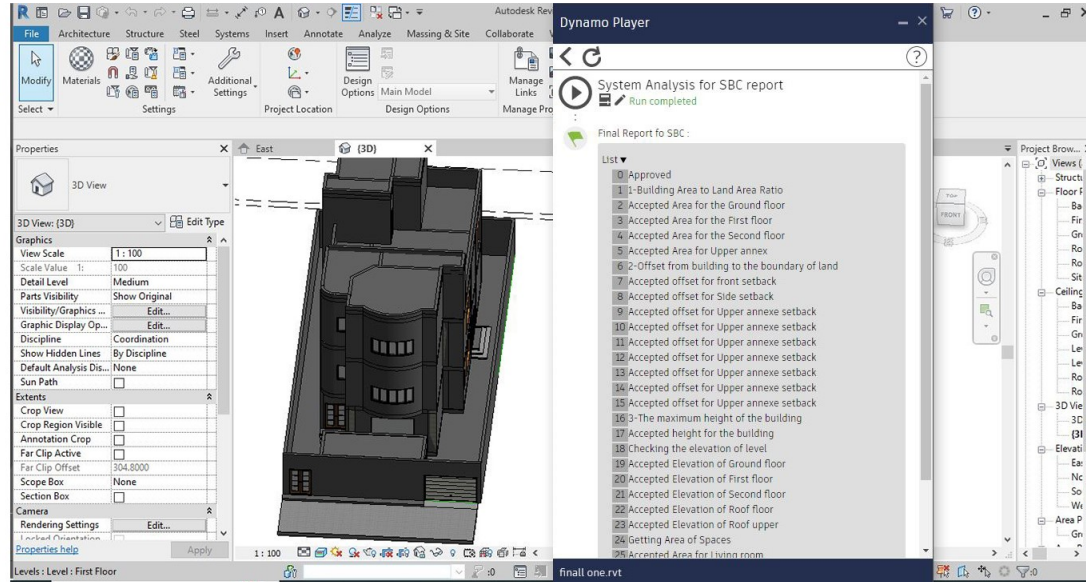
Figure 29 Verification scenarios of the implementation of the framework

Similarly, In the second scenario, the area of the ground floor has been designed to exceed the maximum allowable utilization area of 70%. The aim was to determine whether it could detect non-compliance within the BIM model. The framework accurately detected such non-compliances in the BIM model. The third scenario evaluated how the system handled spatial regulations by modifying the front setback distance from the required 3 meters to an extended 8 meters. This test aimed to assess the system's ability to process geometric adjustments. The framework recalculated the distances but did not approve the extended setback as code compliant. The results underscored the system's adaptability to varying

spatial parameters, proving its flexibility for projects that require customized zoning modifications.

In contrast, the fourth scenario reduced the front setback distance to below the required minimum of 3 meters. This test aimed to evaluate the framework's ability to flag insufficient setbacks that violate code provisions. The system successfully identified the non-compliance and provided actionable feedback, demonstrating its ability to handle edge cases and ensure adherence to critical safety and zoning regulations. In the final test Figure 30 , the framework was applied to a real-world project to assess its performance in a practical setting. The script was executed within the actual project model, and the results confirmed compliance with all relevant SBC regulations, leading to an approved design. This validation confirmed the framework's capability to function effectively beyond controlled test environments, reinforcing its readiness for real-world adoption in the construction industry.

Report in BIM environment



Report on External Excel sheet

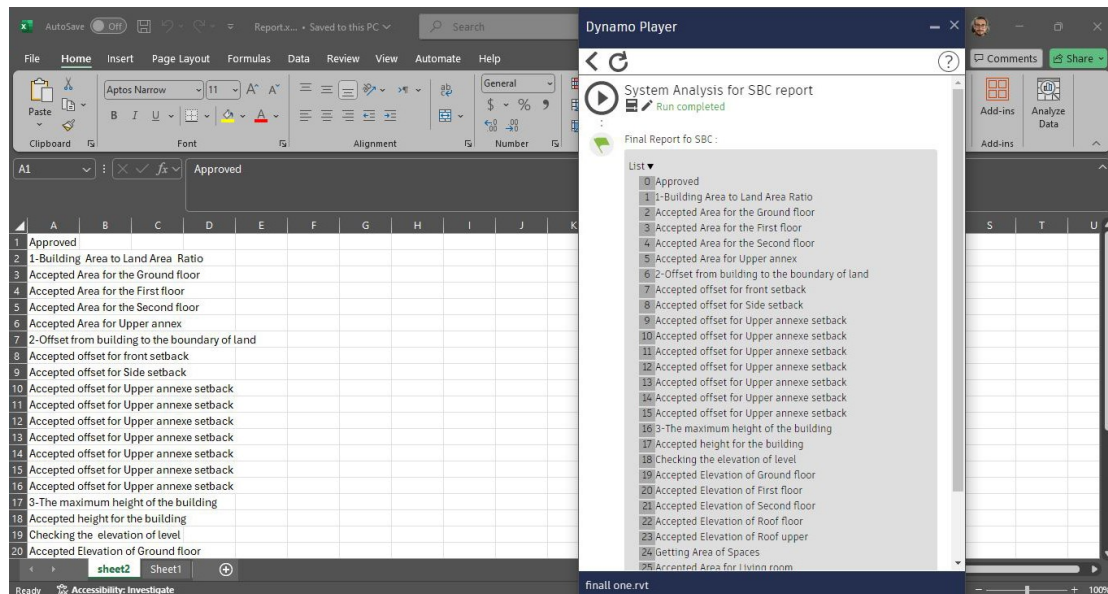


Figure 30 Validation scenario of the implementation of the framework

The following validation of the ACC framework consisted of a consultation exercise with various professionals, such as facility managers, BIM experts, regulatory authors, and building review specialists. Seven professionals participated remotely in the evaluations

where the BIM SBC Tool was used to assess a sample building model. During this exercise, interviewees were guided through the simulation process and provided feedback, which included the following:

1. What is your evaluation of the proposed automatic code compliance, its validation process, and its relevance to the industry?

In general, attendees responded positively to the proposed ACC framework, viewing it as a valuable innovation in both the regulatory and construction sectors, especially in regions with strict building codes like Saudi Arabia. They saw it as a great validation of the concept, underlining that it has the potential to handle such complex regulatory requirements in a very efficient and precise way. Participants stressed above all the flexibility of the framework, which is made possible through the use of VPL. The framework can be modified to meet changing project requirements and building codes. Also, some discussions about its applications beyond residential buildings, with its real-time feedback and user-friendly interfaces improving collaboration among engineers, planners, and regulatory authorities. It includes dynamically generated compliance reports and visualizations that are widely acclaimed as the most efficient enabler of non-compliance identification by stakeholders and subsequent resolution. Further, integration with BIM was claimed as yet another huge advantage, as it automates compliance checking, reduces human errors, quickens document reviews and approvals, and streamline permitting. What is more, it means a contribution to pushing digital transformation within the AEC industry.

2. What are your suggestions for the steps required to implement automated code compliance in the Saudi Arabian construction industry?

Implementing ACC in the Saudi Arabian construction industry requires a structured approach that integrates regulatory standards, advanced technologies, and industry specific practices. The first step is the development of digital rule representation, which involves converting building code rules into structured, machine-readable for creating a database of reusable, categorized rules.

The second step is training and capacity building, which are essential for successful implementation. Workshops and training programs to educate stakeholders, including engineers, architects, and regulatory authorities, on the effective use of the ACC system. Also, by providing clear guidelines for creating BIM models compatible with the tool, ensuring consistency across projects. This step builds the expertise and confidence needed to widely adopt and effectively use the system.

Finally, the ACC system must be embedded into the regulatory framework. This requires collaboration with regulatory authorities, such as the Ministry of Municipalities and Rural Affairs (MOMRA), to integrate the ACC system into existing workflows. Features like automated permit issuance and seamless data exchange between BIM models and regulatory systems enhance efficiency and transparency throughout the approval process.

The implications of implementing the framework for practical applications are substantial. The framework is adaptable, capable of handling changes to inputs and project requirements. It is precise, consistently identifying compliance and non-compliance issues with accuracy. Furthermore, it is practical, as demonstrated by its successful performance in real-world applications. One of its key benefits is the significant reduction in time required to review and approve construction permits, thereby expediting project timelines

and streamlining permit processes. Additionally, it facilitates digital transformation by minimizing human error and enhances accuracy adherence to complex building codes.

Furthermore, the transparency and accessibility of the system fosters better communication and improve collaboration among stakeholders, including designers and regulatory authorities. Its success in handling diverse scenarios also highlights its scalability for broader use cases, such as ensuring compliance with international building codes or integrating with other regulatory domains. In conclusion, the ACC framework has demonstrated great promise in automating compliance checks and adapting to various scenarios. Its flexibility and precision make it a valuable tool for improving efficiency in the construction industry. Future efforts should focus on refining the system further and expanding its capabilities to address a wider range of compliance requirements.

CHAPTER 5

CONCLUSION AND FUTURE WORK

5.1 Summary of the research

The research demonstrates the development and implementation of the BIM-based framework for automated code compliance, an innovative solution for residential building design compliance assessment within the context of Saudi Arabia. The integration of advanced technologies, such as Building Information Modeling (BIM) and Visual Programming Languages (VPL), underscores the framework ability to address long-standing inefficiencies and inaccuracies associated with traditional manual code-checking methods. This user-friendly approach promotes better teamwork, removes the lack of transparency in complex “black box” systems, and increases design flexibility, making the tool dependable for a wide range of users and design standards.

The framework is based on the Design Science Research (DSR) methodology, which ensures a systematic and iterative approach to solving real-world problems. The research identifies critical challenges in current compliance methods, including the misinterpretation of code clauses and inefficiencies in processing permit applications. The Saudi Building Code (SBC) was carefully examined, and techniques like RASE were used to create building code rules that computers can understand and process. These

representations were then integrated into a BIM environment using visual programming tools such as Dynamo, enabling automated rule execution and compliance verification.

This process is achieved in the development of a functional ACC tool, the BIM SBC Tool, that automates compliance checks and provides real-time feedback through Revit environment and external Excl sheet.

The tool delivered real-time feedback for six key building code performance indicators, facilitating compliance with codes such as the Saudi Building Code and supporting early-stage decision-making. The study also outlines the technical steps required for implementing the ACC system, including data collection, rule development, system validation, and practical application. Case studies involving verification and validation residential projects are used to evaluate and validate the framework, demonstrating its ability to accurately assess compliance across key metrics such as building height, room dimensions, setbacks, and window-to-wall ratios. The system further generated comprehensive compliance reports, providing real-time feedback to stakeholders and supporting informed decision-making.

In addition to the technical aspects, the research emphasizes the importance of capacity building and stakeholder engagement. Workshops and training programs are proposed to educate engineers, architects, and regulatory authorities on using the ACC system effectively. Guidelines for BIM modelers are also included to ensure consistency and accuracy in data input. In conclusion, the proposed framework and its implementation signify a paradigm shift in automated compliance verification. By leveraging BIM and ACC technologies, the framework not only accelerates the permitting process but also

enhances accuracy and transparency, aligning with strategic goals Saudi Arabia Vision 2030 broader goals for digital transformation in the construction sector.

5.2 Future work

This study has laid a strong foundation for the development and implementation of an automated code compliance (ACC) system tailored to the Saudi Arabian construction industry. However, there remain several areas of exploration and further development that could maximize the system's potential and broaden its applications. One key area for future work is the integration of qualitative compliance checks. The current framework primarily addresses quantitative requirements of the Saudi Building Code (SBC), such as building height, room dimensions, and setbacks. Expanding the system to include qualitative assessments could enhance its utility by covering design elements that require subjective evaluation, such as aesthetic regulations, fire safety measures, and accessibility standards.

Incorporating emerging technologies like Artificial Intelligence (AI) and Machine Learning (ML) offers another avenue for enhancement. These technologies could improve the system's adaptability and predictive capabilities, enabling more effective rule interpretation and the detection of patterns in building code non-compliance. Furthermore, AI and ML could facilitate dynamic responses to evolving regulatory requirements, making the system more robust and future ready. The development of a unified national database could significantly streamline the compliance process. By establishing a centralized, digital repository of building code rules, case studies, and compliance outcomes, stakeholders such as architects, engineers, and regulatory authorities could access up-to-date

information. This database could be dynamically updated to reflect regulatory changes, ensuring accuracy and consistency across the industry.

Expanding the system to address additional regulatory domains is another important consideration. Currently focused on architectural compliance, the ACC framework could be extended to encompass structural, mechanical, and environmental regulations. Such an expansion would allow for a more holistic assessment of construction projects, ensuring comprehensive adherence to all aspects of the building code. Broadening the system's applicability to a wider range of building types is also essential. While the current study focuses on residential buildings, adapting the framework for commercial, industrial, and institutional structures could significantly increase its impact. This would make the ACC system relevant to a broader spectrum of construction projects and enhance its overall utility.

Lastly, integrating the ACC system with real-time data platforms as part of Saudi Arabia's smart city initiatives could offer significant advantages. Real-time integration would enable dynamic monitoring of construction projects, ensuring compliance throughout the construction lifecycle and aligning with broader smart city objectives.

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