BIM-ENABLED REGULATORY DESIGN RULE CHECKING FOR BUILDING CIRCULATION

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Abstract. Automated design rule checking (RDC) in Building Information Modelling (BIM) can be challenging especially when dealing with qualitative aspects and intricate regulations like building circulation. The study proposes a novel method for Regulatory Design Rule Checking (RDRC) for building circulation, addressing challenges in translating regulations to computational constructs and extracting relevant information from complex BIM models. Through a tiered compliance assessment, the investigation considers preventive rule-based checks for doors and corridors and explores constraint-based regulatory incentive schemes such as through-block pedestrian links (TBPL). The RDRC analysis identifies non-compliance and concludes with a recommendation for potential adjustments. This work aims to benefit designers and regulators, providing productivity enhancements and a deeper understanding of regulatory intricacies in the context of building circulation.

Keywords. Design Rule Checking, Building Information Modelling, Building circulation, Network analysis

1. Introduction

One of the statutory roles of architects, engineers and contractors is to ensure buildings are designed following the local regulations so that buildings are safe and serviceable for their occupants and environmentally sustainable (Dimyadi & Amor, 2013). However, the numerous criteria mandated by various government departments render regulatory compliance checking a time-intensive process traditionally manually carried out by professionals in the Architecture, Engineering and Construction (AEC) industry (Lee et al., 2014; Peng & Liu, 2023). Nevertheless, the use of building information modelling (BIM) offers a significant opportunity for automating design rule checking (DRC) (Eastman et al., 2018) so that designers and regulators can quickly identify non-compliances and make necessary adjustments, increasing the efficiency of compliance checking saving time and resources (Eastman et al., 2009; Choi et al., 2013).

While DRC is not a new concept, its adoption faces two primary obstacles: (a) converting regulations from natural language to computational constructs, and (b)

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correctly identifying and extracting relevant information from the BIM model. Quantitative rules assessing explicit BIM entity properties are straightforward but compliance analyses using implicit information, like circulation paths, are challenging. Circulatory networks, reflecting the routes traversed by people within buildings and urban spaces, is an implicit information derived from the remainder of the building components within a model. In addition, while quantitative aspects of circulation can be defined and measured, evaluating the qualitative aspects, such as ease of access, safety and sufficiency, can be subjective, multi-dimensional and lacking objective metrics (Lee et al., 2009). Hence, determining whether the circulation configuration for a building and its external spaces meets the authorities' requirements requires critical judgment and interpretation, making it a complex task to automate.

This work investigates regulatory design rule checking (RDRC) for building circulation. We address the challenge of identifying circulatory networks by analysing complex BIM databases and translating three-dimensional entities into spatial graphs. RDRC assessment is done using a tiered approach starting from (a) basic compliance testing, (b) deep-insight analysis to identify reasons for non-compliance, and (c) concluding with design recommendations. Our work extends beyond preventive rule-based compliance to explore regulatory incentive schemes which aim to enhance the built environment. We hope our work is useful for designers and regulators by improving productivity and deepening understanding of regulatory frameworks.

2. Relevant Work

The development of rule-based systems in models began in the 1980s (Garrett & Fenves, 1987), and with technological advancements, automated rule checking has progressed but primarily within the research domain (Dimyadi & Amor, 2013). We summarise the various approaches implemented to overcome key challenges in circulatory DRC: (a) rule language, (b) model checking and (c) circulation analysis.

DRC involves translating natural language rules to a computer-readable format. Domain-specific languages are used to extract and parse information from regulations into computer executable code, such as KBim. Another approach is natural language processing which uses artificial intelligence for automatic code generation. Despite these advancements, the ambiguity and complexity of regulations pose challenges for complete automatic conversion into computer code, necessitating human intervention for accurate rule interpretation and translation (Sydora & Stroulia, 2020).

Solibri Model Checker (SMC) is a commonly used DRC software that analyses Industry Foundation Class (IFC) models based on international standards with the flexibility to adjust values to suit local codes (Solibri Inc., 2023). Another example is the e-PlanCheck component in CORENET (Construction and Real Estate Network), a web-based integrated hub for the Singapore construction industry (CORENET, 2016). Both examples use object libraries with coded regulations to check compliance of the IFC models and generate reports, simplifying DRC (Eastman et al., 2009). However, e-PlanCheck has predefined rules that limit users and the report in SMC does not track compliant instances, making it difficult to review which instances have been processed.

Determining a consistent method to represent the paths around the building for circulation analysis is challenging due to varying human movement patterns. A graph-based approach is commonly used due to its simplicity and efficiency (Werner et al, 2000). Various methods have been introduced and the two main types of circulation graphs are (a) topological graphs which show simple room connections without indicating the actual path taken, and (b) distance-measured graphs, which define the circulation path through each space. Traditional methods measure the distance through the center of spaces, while others, like Kannala's evacuation-graph model (2005) and Lee's Universal Circulation Network (UCN) method (2009), propose shortest distance measurements and diagonals to emulate human circulation patterns. We integrate these concepts in our work to create a metric graph structure that provides a unified circulation path through all spaces, following a more natural human circulation pattern.

Various studies have demonstrated the use of circulatory graphs with embedded spatial and physical information for circulatory DRC. The Georgia Institute of Technology developed an SMC plug-in to assess circulation and security compliance for courthouse designs (Eastman et al., 2009; Lee, 2010). Lee et al. introduced Numeric Data of Building Circulation (NDBC) to quantitatively evaluate building circulation by comparing NDBC values of different design options (Lee et al., 2014).

3. Methodology

The process for building circulation RDRC follows a similar four-stage structure that C. Eastman et al. suggest for DRC: (1) rule interpretation; (2) building model preparation; (3) rule application and (4) reporting of results. Based on the four stages, we delve deeper into the specific challenges and considerations associated with each RDRC stage for circulation and mobility within and around buildings.

3.1. RULE INTERPRETATION

Interpreting and translating regulations on circulation and mobility into a computer-readable format poses challenges due to its multiple layers of conditions. To tackle this, a tiered approach is employed sorting the regulations into two groups: simple rules and complex rules. The simpler rules are mostly prescribed preventive quantitative rules and are relatively straightforward to interpret. On the other hand, complex rules are commonly qualitative constraint-based regulations and may require the consideration of multiple conditions before a check can be done. For instance, the minimum covered walkway width varies according to its location. Qualitative regulations are usually more complicated as they tend to lack clarity. For example, the regulation may state that a public space should have frontage onto a major street or pedestrian thoroughfare which is difficult to define. To deal with the complexity, the rules are broken down into parts to ensure the nuances and intricacies of the regulations are captured accurately and that the computerized version reflects the original intent and meaning.

3.2. BUILDING MODEL PREPARATION

Standardised BIM models are crucial to facilitate the extraction and utilisation of the relevant information for building circulation RDRC. Unfortunately, there is a lack of quality control as many do not adhere to the modelling conventions or best practices, (Migilinskasa et al. 2013; Wang et al. 2014; Chen and Luo, 2014). Some examples include (a) misuse of modelling object-model such as using a floor-type object to model the roof, (b) limitations of BIM object-model such as roads and urban features, (c) partial or incorrect labelling entities with non-standard categorical data such as door width can be stored as “width” or “rough width”, (d) inconsistent use of geometric and semantic information such as elevators or parking lots can be modelled as floors, lines or hatches, and (e) modelling errors such as unenclosed spaces with gaps between walls or walls and floors. Consequently, identifying the appropriate elements for checking and preparing the model for data extraction becomes more problematic.

For this purpose, we developed an application to automatically extract the essential information from the model to generate the implicit circulation path for circulatory RDRC. The application reconstructs the 3D model into 2D polygons with assigned attributes to identify the elements (e.g., walls, doors or windows), their properties (e.g., opaque or porous, indoors or outdoors) and the type of space (e.g., shop, restaurant, toilet or stairs), see Figure 1. However, due to modelling inconsistencies, much manual polygon reconstruction is required. To compute the circulatory graph for analysis, the polygons are skeletonized using the Medial Axis Transform. This graph transverses through the middle of all walkable spaces and doors, see Figure 1, and is composed of nodes and edges with embedded physical data organised in Python dictionaries.

Figure 1. Extraction of circulation paths from BIM model: (a) Perspective plan view of 3D model. (b) Reconstructed 2D polygons. (c) Extracted circulatory graph through walkable spaces

3.3. RULE APPLICATION

Using the extracted spatial properties and attributes of the model's circulatory graph, the design is checked for compliance. The circulatory RDRC is formulated and implemented in a Python notebook using NetworkX functions to analyse the extracted circulation paths. Depending on the complexity of the rules, the execution process and required data for rule checking may vary. Typically, RDRC for simple quantitative rules, such as minimum or maximum dimensions for a particular element, can directly utilise the data in the dictionaries of the relevant nodes and edges. Advanced rules with multiple requirements will need to be broken down into parts for analysis and additional analytical steps to derive implicit properties from the model. For example, determining the shortest distance to an exit door would require identifying the nearest exit door and measuring the distance from that room to the exit door.

3.4. REPORTING OF RESULTS

This final step reports the results of the rule checking, identifying which elements have passed or failed the requirements of the rules. We use Matplotlib in Python to generate graphical reports which visualise the items that passed or failed the regulations at their location. Additionally, further classification to indicate the severity of the violations can be implemented, such as colour coding, numbering or other means. This allows designers to promptly identify the areas that require rectification to ensure compliance.

4. Results

Based on the proposed methodology, the application of RDRC for circulatory-related rules in Singapore has been tested on various typologies. The BIM model of a shopping mall in Singapore is used as a case study to exemplify the complexity, approach and any assumptions made.

4.1. BASIC COMPLIANCE TEST

The circulatory RDRC assessment starts with simple prescriptive quantitative regulations. An example applicable across most countries would be a minimum door or corridor width requirement. Under Singapore's regulations, the minimum clear opening of doors is 850mm and the minimum width of corridors is 1200mm. These design parameters are set to ensure that the functionality of the doors and corridors is met and adequately sized for the occupants to pass through.

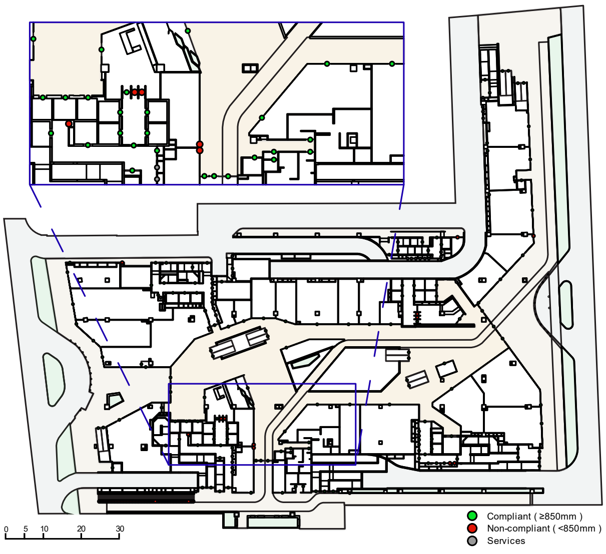

Figure 2. Checking for door compliance

Door width RDRC is a relatively straightforward task since the doors are specific object types with fixed dimensions. Using the extracted circulatory graph, all door nodes are filtered out and their width is checked if they meet the minimum width requirement. The results are visually reported in a plan to show which falls below or meets the minimum, see Figure 2, enabling designers to quickly identify areas that need rectification. Moreover, there may be additional conditions that affect the minimum door width requirement, such as the type and capacity of the room which the door leads to. For instance, cabinet or riser doors, although considered doors within the model, are exempt from following the minimum width requirements. Consequently, each door node has attributes which accurately identify the destination of the door to allow a more precise investigation, corresponding to its minimum door width requirements.

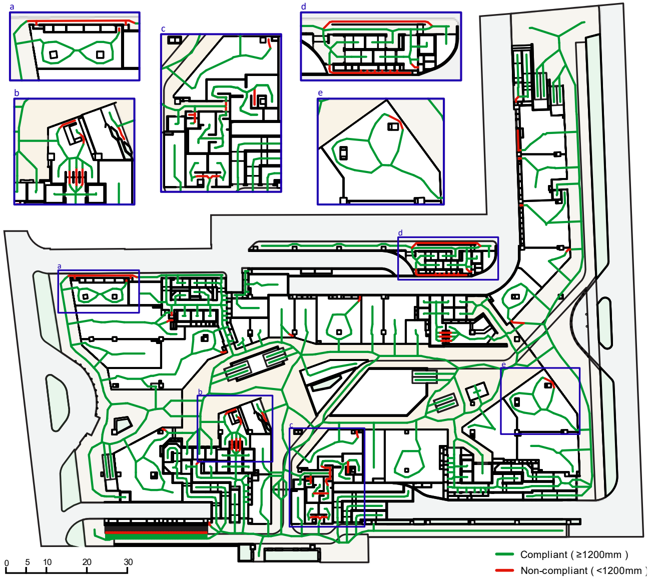

Figure 3. Checking for corridor compliance

On the other hand, corridor widths are not readily available and checking for compliance requires additional effort. Corridors are typically a straight passage formed between two parallel walls that provide access to various rooms. However, there may be instances where the space is irregularly shaped and the widths vary. Therefore, it is crucial to measure the widths of all circulation spaces to pick up potential areas that do not meet the regulatory requirements. Our circulatory graph representation derives the central line within all spaces and the measured dimensional information at the ends of each edge is stored in the node attributes, allowing us to evaluate the width of all the network paths. Similar to the assessment and reporting process for the door widths, corridors which violate the rules are filtered and highlighted, see Figure 3.

4.2. THROUGH-BLOCK PEDESTRIAN LINKS

Through-block pedestrian link (TBPL) is a regulatory incentive scheme by URA that encourages better urban circulatory design. TBPL is a pathway that cuts across a private development increasing ground-level permeability, creating an extension of the public space, increasing connectivity between public spaces and enhancing pedestrian convenience by shortening distances travelled.

Technically a TBPL is defined as “an internal covered walkway space between 4m to 7m wide that runs through a building, connects two parcels of public areas and is always kept open for public use”, (URA, 2020) as depicted in Figure 4. According to the code, all covered floor areas within a development are counted as gross floor area

(GFA) and are taxable unless exempted, meaning TBPL areas are also taxable. Hence, developers tend to avoid wide corridors or walkways in their projects since these circulation spaces are not commercially lucrative as they are non-rentable and non-sellable spaces. Therefore, to incentivise designers and developers to incorporate TBPL in their developments, the calculation of taxable GFA for compliant TBPL is excluded. The specified minimum width ensures sufficient space for pedestrians' comfort, preventing narrow corridors. Simultaneously, the maximum width ensures excessive corridor size and prevents exploitation of the incentive.

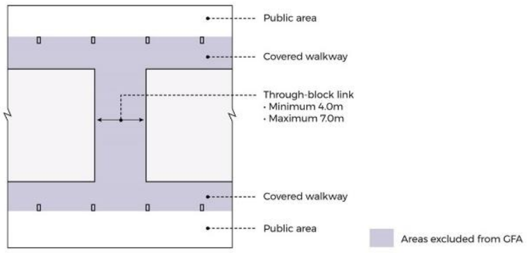

Figure 4. Explanatory concept diagram showing a plan view of Through-Block Pedestrian Link (TBPL) from Covered Walkway and Linkages, by Urban Redevelopment Authority, 2023.

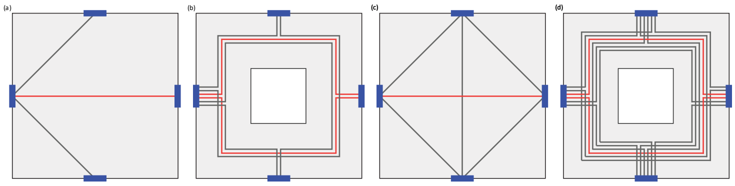

Figure 5. All routes from one door to all doors: (a) in a space without cycles vs (b) in a space with cycles. All routes between all doors: (c) in a space without cycles vs (d) in a space with cycles

Since the TBPL is a constraint-based regulation and is generally annotated in the submission plans by the architect, there is no certainty whether it is correctly done. For both architects and regulators, the verification of the validity of TBPL is non-trivial and should not be overlooked. Hence, the challenge from the perspective of DRC is (a) Determining what spaces may be a candidate for TBPL; this implies filtering out private from quasi-private spaces based on room usage. (b) Determining what source-destination pairs for the doors; differentiating the main and service doors. (c) Computing all possible routes between them; for which spaces without internal circulatory cycles, it is a quadratic complexity problem, O(n2), where 'n' represents the number of doors. However, when dealing with spaces containing cycles, the complexity quickly escalates to factorial, O(n!), refer to Figure 5.

Determining the potential public spaces for the TBPL can be inferred by either (a) using the architect's annotation or (b) selecting the spaces with the highest concentration of doorways. The latter heuristic is highly effective as lobbies and common building areas tend to have at least one order of magnitude higher number of doors compared to regular rooms, see Figure 6. To determine which doors are suitable to perform TBPL analysis we may either (a) use the architect's annotation as to which constitute main entrances or (b) infer those from space usage characteristics. To efficiently compute the TBPL we perform a route filtering by pruning the interior graph of the space to exclude all ineligible edges, as shown in Figure 7. This simplification reduces the computational complexity of finding all simple paths between source-destination pairs. Simple paths are paths in a graph that does not have repeated nodes and is suitable since the TBPL should not go in a loop. For instance, in the case study, the number of all simple paths without filtering is 2016 while after the filter is 20, computed in 6346 milliseconds and 27 milliseconds, respectively.

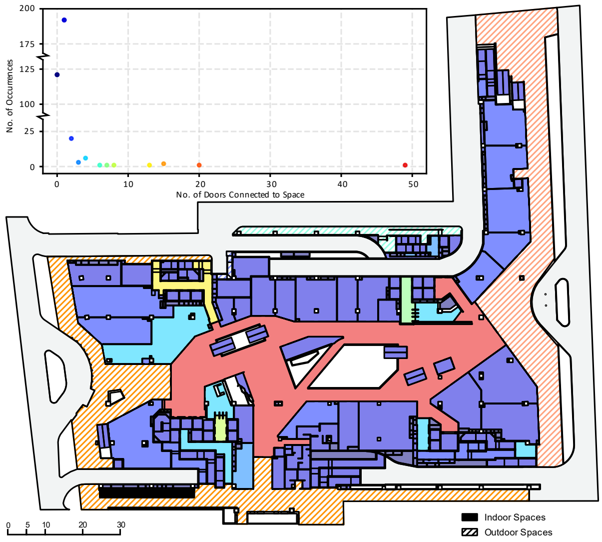

Figure 6. Comparison of number of doors per space

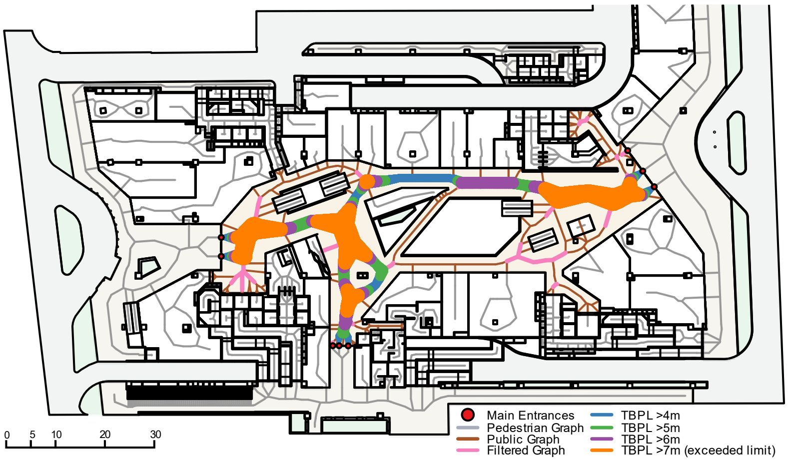

Figure 7. Filtered Graph that identifies all unique and valid TBPLs

Besides successfully accomplishing the primary goal of identifying all unique and valid TBPLs, as shown in Figure 7, our investigation uncovers additional observations related to code interpretation and design feedback. The following are our key findings from the analyses and insights of our research: (a) There may be more than one TBPL in a building which is interesting since it is not assumed in the code. (b) We can determine the straightness of a TBPL which is implied by the URA diagram, Figure 4, but not explicitly mandated. As seen in Figure 7, the identified TBPL is not straight but goes through a few bends and curves. (c) Our research provides valuable design feedback to architects, offering insights into paths that are potential TBPLs but are interrupted by local bottlenecks. (d) Finally, we can evaluate and compare the efficiency of the TBPL by computing the GFA gained or lost in the process. Through our research, we have provided a more measured approach to assess and evaluate the TBPL which offers insights to both regulators and designers.

5. Conclusion

In conclusion, we have presented a systematic approach to building circulation RDRC and demonstrated a plausible solution to resolve the issues faced. The study introduced a method for extracting circulation paths from BIM models and used the spatial structure of the graph to perform circulatory RDRC assessment for both conventional preventive rule-based compliance and regulatory incentive schemes. Achieving better BIM standardisation and quality control is crucial to fully automate the generation of the circulation network from BIM and reduce manual intervention. The extracted circulatory graph has the potential to be employed in various network analyses such as identifying the heavily traversed paths and assessing corridor capacities to prevent crowding.

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