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DOI:
10.1002/tal.1946

Publication date:
2022

Received: 2 December 2021 | Revised: 22 February 2022 | Accepted: 4 May 2022

DOI: 10.1002/tal.1946

RESEARCH ARTICLE

WILEY

A preliminary design tool for volumetric buildings

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Funding information
Malaysia Ministry of Higher Education, Grant/Award Number: FRGS/1/2021/TK01/SWIN/02/1

[Correction added on 08 July 2022, after first online publication: CAUL funding statement has been added.]

Summary

Volumetric building (VB) is a type of off-site construction to move towards high productivity construction. Literature review shows that there are only few models for upstream feasibility study for VB, while many researchers delved into advanced structural engineering aspects of VB modeling (i.e., downstream detailed and technical design). However, there is a lack of guidance for the preliminary design of VB, which is an essential stage that falls in between upstream feasibility study and downstream detailed and technical design. Hence, this paper is written to fill that gap by proposing a new design tool for VB, anchored upon the "desire path" philosophy, which is often used in urban planning, that is, natural formations evident from preceding experiences. Literature review also shows that a comprehensive VB database is not available. Hence, a new database is collected with 31,185 units of modules and 911 module types, sourced from VB projects worldwide to provide a broad global overview. The proposed tool has a systematic framework of a four-quadrant plot for preliminary VB design, enabling designers to determine the number of modules, size of modules, massing typology, and module construction material through new empirical relationships.

KEYWORDS

database, modular building, off-site construction, preliminary design tool, volumetric building

1 | INTRODUCTION

Off-site construction is recognized as a promising strategy for productivity improvement in contemporary building construction.[1–4] Generally, off-site construction involves prefabrication of building elements in an off-site manufacturing plant, followed by transportation and on-site assembly to form a functional building.[2] Depending on the degree of prefabrication, off-site constructed building is generically categorized into three levels, that is, elemental, planar and volumetric, as shown in Figure 1. An elemental building consists of one-dimensional (1D) linear precast members such as beams and columns, whereas a planar building is constructed from off-site manufactured two-dimensional (2D) diaphragms such as walls and slabs. Various literature had proven the superiority of volumetric adoption (or modular construction) in terms of construction speed,[5–8] cost-effectiveness,[7,9] and sustainability.[10]

The industry is moving towards high productivity construction such as volumetric building (VB) construction to address skilled labor shortages in many countries worldwide. Contradictory to common perceptions of container-like outlook, recent applications of VB are architecturally flexible and esthetically pleasing and could be used for high-rise building construction (see examples in Figure 2). These VBs are branded differently across regions, for example, Hickory Building System (HBS) in Australia,[11] Prefabricated Prefinished Volumetric Construction (PPVC) in Singapore,[1] and Modular Integrated Construction (MiC) in Hong Kong.[4]

It is noted that VB adoption remains a challenge, especially for stakeholders who are familiar with conventional construction.[12,13] Despite having many VB projects completed, detailed VB implementation strategy information at a preliminary design stage is often inaccessible, as it

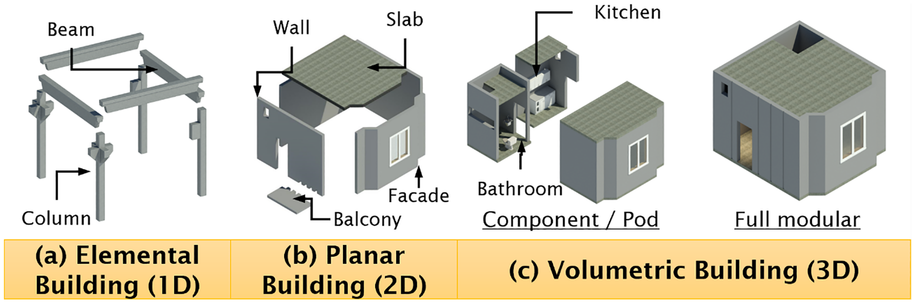

FIGURE 1 Three levels of off-site constructed building

FIGURE 2 Examples of recent high-rise VB

remains commercial in confidence. As a result, substantial financial investment is required to engage knowledge and guidance from experienced market-leading players. This process which involves stakeholder engagement, including meetings and site visits, is often inefficient and inconclusive in obtaining VB solutions and insights.

Given the challenges of obtaining information for VB implementation and lack of written guidance for preliminary design of VB, this paper is written to fill that gap by formulating a "desire path"-inspired design tool to establish some essential parameters for a VB project, for example, number of modules, size of modules, massing typology, and construction material in relation to various gross floor areas. The "desire path" philosophy (i.e., natural formations evident from preceding experiences) is used to provide experience learnt in past VB projects. The proposed design tool is expected to facilitate the preliminary design process of VB for stakeholders who are more familiar with conventional construction.

2 | EXISTING DESIGN GUIDANCE FOR VB

Scarcity in VB design guidance remains one of the dominant inhibitors of VB implementation.[12] Hayes[14] claimed that VB design is challenging and distinctively different from that of conventional structure, as modularization factors and other considerations such as transportation and logistics planning govern the design. A systematic VB implementation process can be referenced to the typical building design process outlined by the Royal Institute of British Architects[15] or RIBA, which can be further generalized into feasibility study (RIBA Stage 1, referred as the upstream process in this paper), preliminary design (RIBA Stage 2, the focus of this paper), followed by detailed and technical design (RIBA Stage 3 and 4, referred as the downstream process in this paper) as shown in Figure 3.

During the feasibility study, the viability of the VB technology to be applied to a project site is often assessed based on the client's requirements and project constraints. Recent publications have provided recommendations for implementing VB feasibility studies; for instance, Lu et al.[16]

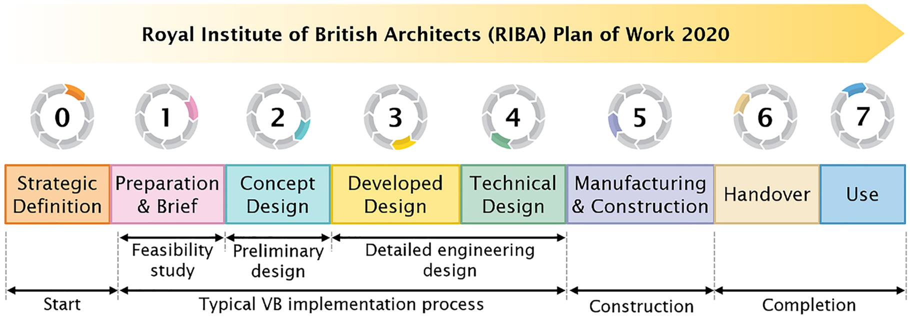

FIGURE 3 Typical VB design process according to RIBA Plan of Work 2020

proposed a PEST (political, economic, social and technological) environment-driven analytical framework to identify the optimum prefabrication level. Thirteen PEST factors were identified from the literature, and feasibility scores were assigned accordingly by experts for feasibility evaluation.[16] A survey knowledge-based decision support system for PPVC was introduced by Hwang et al.[17] The system was capable to assess the suitability of PPVC to a certain project based on distinctive decision-making factors for VB adoption, which were collected from the literature, and verified against the answered questionnaires by diverse experts. An MiC feasibility stage-gate model was developed by Wuni and Shen[18] from identified decision-making factors. In contrast to previous rating-based feasibility studies, the developed model provided a robust and systematic decision-making process for MiC. Mather and White[19] proposed a multimetric feasibility evaluation tool for VB design to minimize cognitive biases during the decision-making process. This tool provided a rating-based feasibility review for off-site construction options using an interactive decision dashboard. In brief, guidance for VB feasibility study for decision making is founded mainly on a rating-based methodology obtained from literature and survey.

Once the VB technology has been decided, a preliminary design for VB is to be carried out to provide a conceptualized design to meet the client's needs and site-specific constraints. The existing literature for VB preliminary design is mainly focusing on design optimization and lesson learned from case studies. Salama et al.[20] proposed a near-optimum VB configuration method, considering preliminary design parameters such as connections, logistics, transportation cost, and material usage. This method offered rapid identification of near-optimum VB configuration based on indices ranking for several design schemes. However, manual spatial design is required as there is no suggestion for the number of modules and VB layout on a floor plan. Hence, Sharafi et al.[21] automated the optimization of VB preliminary design with spatial design. The VB model was discretized and expressed using a design structure matrix, followed by Ant Colony algorithm optimization, with preliminary design parameters such as construction cost and energy efficiency considered. Lawson et al.[7] documented practical industrial case studies and a comprehensive overview was provided as a guide. It was found that the selection of exterior post modules offers better flexibility in room layout planning. Hough and Lawson[22] extended the scope to four high-rise VBs in the United Kingdom, with construction details reviewed. Useful design considerations such as module dimensions and the use of core walls for VB stability were highlighted. However, there is no specific design tool recommended. Interestingly, a case study in New York claimed that effectiveness of VB design is closely related to the trip count of module transportation due to traffic regulation.[23] Gardiner[24] showed that selection of module construction material was greatly influenced by the regional climate condition, based on VB construction experiences in Darwin, Australia. A comprehensive review of 35 critical success factors for VB design consideration was also reported by Wuni and Shen[25] to facilitate VB implementation.

In the final design stage, the VB preliminary design scheme is to be refined and enhanced with engineering and manufacturing considerations to form a detailed design. The Building and Construction Authority (BCA) of Singapore published a PPVC guidebook on design, prefabrication and installation.[26] In Australia, a design handbook was published for VB engineering design with reference to the Australian design code and Eurocode.[27] A VB construction specification was recently drafted by China Association for Engineering Construction Standardization for VB adoption in China.[13] Several engineering research topics were actively discussed, including construction tolerances,[28,29] inter-module connection modeling,[30–32] and structural analysis methods.[5,33]

The literature review clearly shows a lack of guidance for the preliminary design of VB (RIBA Stage 2), which is an essential stage that falls between the upstream feasibility study (RIBA Stage 1) and the downstream detailed and technical design (RIBA Stage 3 and 4). This paper aims to provide a design tool for the preliminary design of VB to assist stakeholders in establishing parameters such as the number of modules, size of modules, massing typology, and module construction material.

3 | METHODOLOGY TO COLLECT THE DATABASE OF VB PROJECTS

Literature review shows that a comprehensive VB database is not available. Hence, an up-to-date database of 31,185 units of modules and 911 module types, sourced from VB projects worldwide to the best of the authors' ability, was compiled in terms of gross floor area (GFA) of project, building, story and module, in view of the strong correlation between them (to be demonstrated in subsequent sections). This database forms the recommended feasible design envelopes and some empirical relationships to be used in conjunction with the proposed design tool in this paper. The methodology of the database collection includes data sourcing, calibration, and verification, as illustrated in Figure 4. The VB data was sourced globally without bias of countries or companies, preferably from reliable architectural, structural, and construction drawings, or in some situations, the property developers' unit sales plans and Google Earth satellite map.[34] The architectural, structural, and construction drawings were typically acquired from local municipal open database (e.g., Department of Planning, Lands and Heritage (DPLH) Western Australia[35] and Aberdeen City Council[36]). In the absence of technical drawings, secondary data from the property developers' unit sales plan was used instead. For further missing data, reconstructed floor plans were calibrated with the dimensions obtained from Google Earth satellite image.[34] An acceptable tolerance of 100 mm was set for the length and width of modules by comparing the average dimensions of the reconstructed floor plan with map data. The maximum error was about 4% for length and 6% for width of modules. Next, the collected and processed database was verified against reported geometry information in the literature and guidebooks. Simultaneously, visual comparison between the processed data with construction time-lapse media was carried out to further validate the credibility of the database. VB projects that had discrepancies from the processed data from different sources were excluded from the database.

Table 1 shows a summary of the VB projects collected in the database. The dataset consists of 31,185 units of modules, 911 module types, and 77 building blocks sourced from 40 VB projects worldwide. The database collection is a daunting task, as the information is not publicly available, and many remain commercial in confidence. The projects with a footnote[a] consist of multiple tower blocks of VBs in a single project. Low-rise VBs, taken as less than three stories, have been disregarded in this assessment, as the number of modules is not significant compared to taller buildings with more modules. Importantly, only mass production of module can achieve economies of scale in larger and higher VB projects. The collected VB projects were codenamed based on regional groups; for example, AS is the codename for Hong Kong, Malaysia, and Singapore; EU is the codename for France, Germany, Spain, and United Kingdom; NA is the codename for Canada and the United States; OC is the codename for Australia. The collected VB database can be made available upon request by the readers.

Figure 5 provides an overview of the database distribution according to the functionality of VB projects and construction materials used for the modules. For functionality, the VB database is largely dominated by residential projects, that is, apartments, condominiums, and student dormitories. Other functions include commercial projects (which are mainly hotels) and mixed development. The typical construction materials of the modules are concrete and steel, with the exception of several projects with modules constructed using engineered timber and steel-encased concrete (composite).

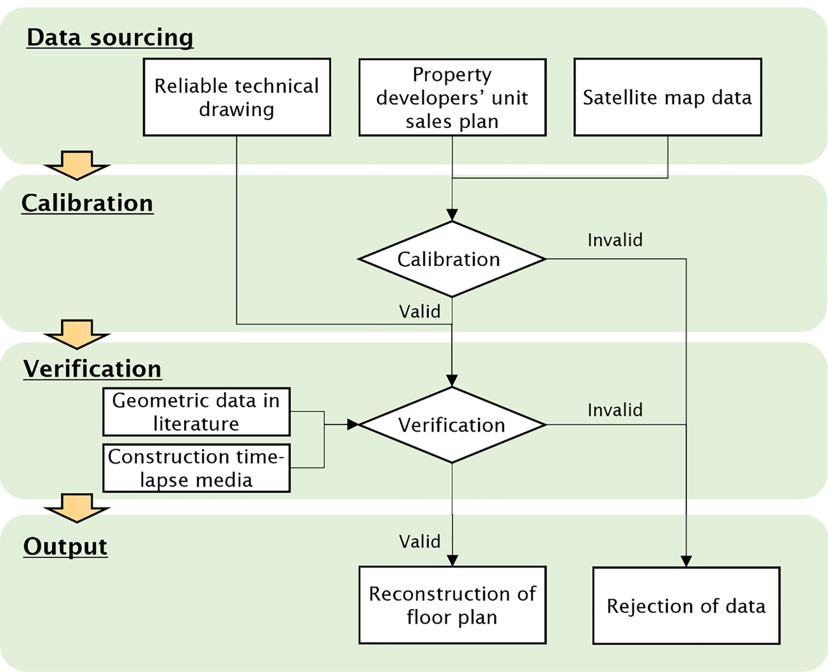

FIGURE 4 Methodology of VB data collection

TABLE 1 Summary of the VB projects included in the database

Project code	Project name	Address
AS001	Disciplined Services Quarters[a]	Area 106, Pak Shing Kok, Tseung Kwan O, Hong Kong.
AS002	HKU Student Residence[a]	Police School Road, Wong Chuk Hang, Hong Kong.
AS003	The Clement Canopy Condominium[a]	16 Clementi Avenue 1, Singapore.
AS004	The Brownstone Executive Condominium[a]	150-164, Canberra Drive, Singapore.
AS005	Wisteria Condominium[a]	590-596 Yishun Ring Road, Singapore.
AS006	Parc Riviera Condominium[a]	103 West Coast Vale, Singapore.
AS007	The Tapestry[a]	51-63 Tampines Avenue 10, Singapore.
AS008	West Terra HDB[a]	450-451 Bukit Batok West Avenue 6, Singapore.
AS009	Spring Valley HDB[a]	478-479 Yishun Street 44, Singapore.
AS010	Kwasa Damansara City Centre Showroom	Seksyen U4, Shah Alam, Selangor, Malaysia.
EU001	Apex House	23 Fulton Road, Wembley, United Kingdom.
EU002	Dexion House[a]	2-4 Empire Way, Wembley, United Kingdom.
EU003	Former Essex House[a]	101 George Street, Croydon, United Kingdom.
EU004	Addiscombe Grove CR0	28-30 Addiscombe Grove, Croydon, United Kingdom.
EU005	Sail Street SE11	8 Sail Street, London, United Kingdom.
EU006	The Glassworks	Coquet Street, Newcastle, United Kingdom.
EU007	Hampton by Hilton Aberdeen Westhill	Straik Road, Elrick, Westhill, Aberdeen, United Kingdom.
EU008	Woodie	Dratelnstrasse 32, Wilhelmsburg, Hamburg, Germany.
EU009	Residencia Gaston Phoebus	12 Avenue du Doyen Robert Poplawski, Pau, France.
EU010	VPO Banyoles	153 Carretera de Vilavenut, Banyoles, Girona, Spain.
NA001	Altantic Yards B2	461 Dean Street, Brooklyn, New York, United States.
NA002	CitizenM Hotel Bowery	189 Bowery, New York, United States.
NA003	2044 Franklin	2044 Franklin Street, Oakland, California, United States.
NA004	The Stack	4857 Broadway, New York, United States.
NA005	Carmel Place	335 East 27th Street, New York, United States.
NA006	AC Nomad Hotel	1170 Broadway, New York, United States.
NA007	38 Harriet Smartspace	38 Harriet Street, San Francisco, California, United States.
NA008	Trinity Western University Jacobson Hall	7600 Glover Road, Langley, British Columbia, Canada.
NA009	Othello Apartments	7339 43rd Avenue South, Seattle, Washington, United States.
NA010	CitizenM Seattle	201 Westlake Avenue North, Seattle, Washington, United States.
OC001	Little Hero Apartment	16-30 Russell Place, Melbourne, Australia.
OC002	Pegasus Apartments	435-439 Whitehorse Road, Mitcham, Victoria, Australia.
OC003	3East Apartments	37-39 Bosisto Street, Richmond, Victoria, Australia.
OC004	Port View Apartments	2 McKay Street, Port Hedland, Western Australia, Australia.
OC005	One9 Apartments	19 Hall Street, Moonee Ponds, Victoria, Australia.
OC006	Unilodge Darwin	6 Dripstone Road, Casuarina, Darwin, Northern Territory, Australia.
OC007	SOHO Apartments	31-33 Woods Street, Darwin, Northern Territory, Australia.
OC008	La Trobe Tower	323 La Trobe Street, Melbourne, Victoria, Australia.
OC009	Tribe Adelaide	124 Wakefield Street, Adelaide, South Australia, Australia.
OC010	Ibis Styles East Perth	69 Adelaide Terrace, East Perth, Western Australia, Australia.

Note: This is not an exhaustive list, with last update in July 2021. The collected VB database can be made available upon request by the readers.
AS Regional group codename for Hong Kong, Malaysia and Singapore.
EU Regional group codename for France, Germany, Spain, and United Kingdom.
NA Regional group codename for Canada and United States.
OC Regional group codename for Australia.
[a]Multitower development project.

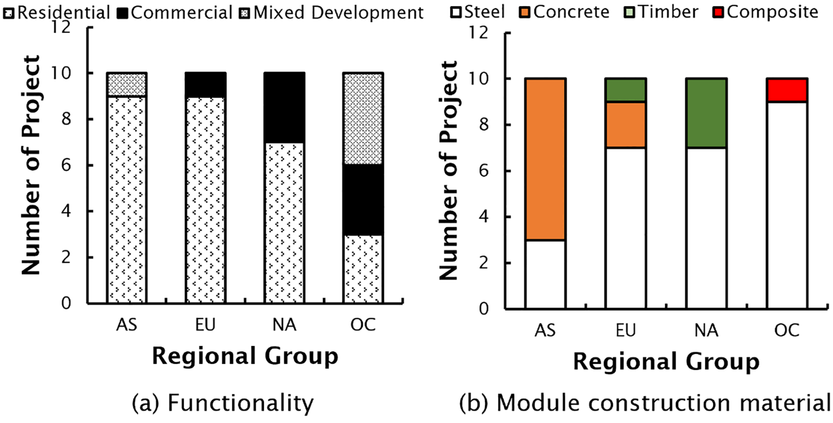

FIGURE 5 Distribution of the collected VB database according to functionality and module construction material

4 | HIERARCHICAL REVIEW OF MODULE DIMENSIONS, BUILDING MASSING TYPOLOGY, AND DEVELOPMENT SCALE

Based on the collected database, three levels of hierarchical reviews are described in this section in terms of module dimensions, building massing typology, and project development scale.

4.1 | Dimensions of module

Past research claimed that dimensions of modules are largely governed by crane lifting capacity and dimension of transportation vehicle.[20,37] The weight of the module depends on the module construction material, typically ranging from 15 to 35 tons, while the crane lifting capacity available in the market is approximately 25 to 40 tons.[26] Nevertheless, a module that exceeds 20 tons is not advised, as it may cause a dramatic increase in lifting cost.[37] The progressive development of lightweight material[37,38] could lower module weight without compromising the module dimension. Hence, the exact module weight in VB design is not considered in the database and disregarded in developing the proposed design tool. However, it is found that the module dimension is controlled by regional transportation regulations and facilities. For public safety on the road, a permit or police escort is usually required when transporting oversized modules and the module dimension must also abide by the maximum allowable vehicle dimension specified by local authorities. For modules exported internationally as freight, the module size is further controlled by shipping regulation.[39] Other considerations about road facilities such as bridge or underpass clearance are crucial for determining module dimensions. Whisker box diagrams are plotted for the 31,185 datasets of modules (911 module types) collected in the database according to module construction materials (see Figure 6) to facilitate the discussions on dimension distribution (width, length, and height) of existing modules across regional groups.

4.1.1 | Module width, W_m

Typically, the module width (W_m) is found to lie within 2.5 to 4.8 m, as shown in Figure 6a. The module width is observed to have some degrees of uniformity within a regional group, evidently shown by the small differences of the medians of different material. This indicates that the choice of module materials has little effect on the selection of module width during the design stage. On the contrary, there is a slight difference in module widths across regional groups, which could be logically explained by the influences of local transportation regulations and facilities. It is noted that the module is commonly sized to a width that could be fitted into a single lane carriage to avoid the need of applying for a special permit or police escort. For example, the Land Transportation Authority (LTA) in Singapore allows module transportation without a permit, provided that the width of the module is smaller than 3.4 m[37]; VicRoads in Australia has a slightly higher allowable width up to 3.5 m. Interestingly, despite the little difference of allowable width, the modules in regional group OC commonly exhibit a larger width than regional group AS. Hence, this suggests that compliance to allowable width without police escort is advisable but may not be obligatory. As a rule of thumb, the preferred width of a room module is approximately 3 m to fulfill architectural needs, while a bathroom pod could be designed to be narrower. An oversized module is used where large width is required (e.g., luxury penthouse in premium property).

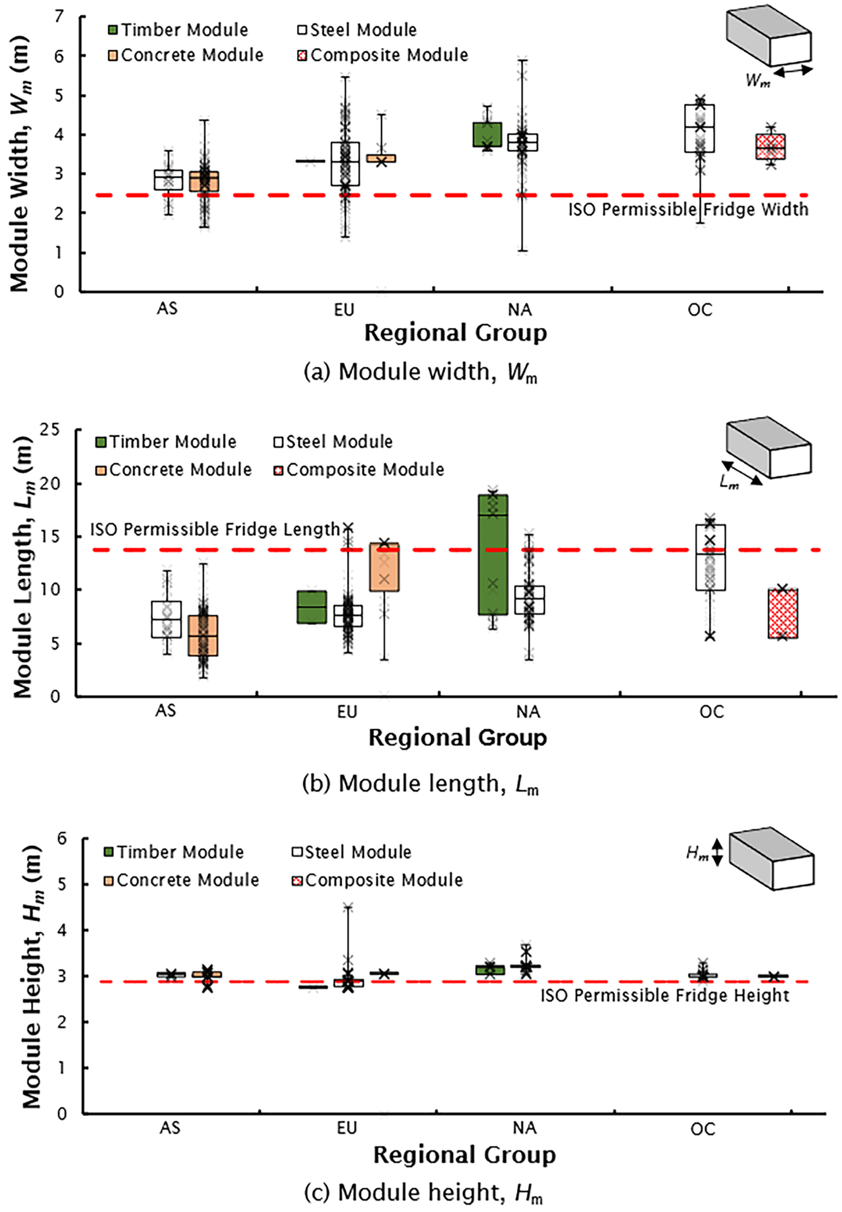

FIGURE 6 Dimensions of the 911 module types designed in different regional groups

4.1.2 | Module length, L_m

In contrast to module width, module length (L_m) is greatly affected by the selection of construction materials. As illustrated in Figure 6b, the module length within a regional group is found to vary across different materials. This variation is postulated to be closely related to strength-to-weight ratio of the material, which has a great impact on the architectural spatial arrangement for VB. For instance, a bulky wall-supported concrete module in regional group AS is generally designed as a functional component or pod (see Figure 1c), with a shorter span to accommodate its unique functionality such as bathroom or kitchen. Alternatively, the application of higher strength-to-weight ratio materials such as engineered timber and steel can also accommodate designs of longer modules up to 20 m. Hence, bedroom and bathroom or living and dining room can be combined to form one longer module. A two-bedroom unit is often arranged in a single module with a corridor sandwiched in the middle along the length, particularly for student dormitory applications. There are attempts in extending the module length of concrete module by reducing its self-weight. For example, concrete column-supported module is used to replace heavier wall-supported concrete module in regional group EU, leading to greater module length of up to 14 m.

The local transportation regulation and facilities also govern the module length and the imposed regulation on permit requirements for police escort or maximum length restriction are well-reported in the literature.[20,37] It is noted that these regulations are applied to vehicle dimensions rather than the module itself and the readers are reminded that the trailer head dimension needs to be considered in determining the allowable module length to comply with the regulation. Besides, the considerations of existing transportation facilities such as influence of horizontal turning radius coupled with speed of trailer inducing centrifugal acceleration force[40] and tunnel accessibility are critical to determining the upper limit of module length.

4.1.3 | Module height, H_m

As observed in Figure 6c, module height (H_m) is the least varying dimension compared to width and length. The typical height is found to be 3.0 m to 3.2 m. The consistency in module height across regional groups and module materials suggests little relationship between the height with local transportation regulations and choice of module materials. This uniform height is likely due to the typical minimum room height in building design. However, some outliers are observed at 4.5 m. These modules with extra height are found to serve special applications, for example, mechanical room and premium penthouse on the rooftop. Hence, vertical clearances at underpass, tunnel, and overhead power line need to be taken into consideration.

In summary, module dimensions of width, length, and height should always comply with the maximum vehicle size specified by local authorities, while permit or police escort is required for transporting oversized modules in some cases. Some literature highlighted the need for compliance to International Organization for Standardization (ISO) permissible freight container size for module design,[20,39] which are drawn with red dash lines in Figure 6. Interestingly, existing module dimensions were rarely designed to comply with ISO freight container size. Considering the findings presented in this section, it is recommended that VB designers could make use of module length (rather than module width and height) in optimizing module weight with the choice of construction materials.

4.2 | Massing typology of VBs

At building level, the relationship between load-bearing modules and lateral force-resisting structural system of VB are classified into four categories of massing typologies, that is, linear, spinal, cluster, and centric (see Figure 7). In Figure 7a, a linear VB typically consists of a series of interconnected modules arranged linearly in line,[41] while existence of strong lateral force resistance system (e.g., shear wall and core wall) is optional. For a system without shear walls, inter-module connections for load transfer between modules in forming moment frame actions are essential. Figure 7b shows a spinal system consisting of a central core wall with a corridor system connected to multiple interconnected modules.[7] This results in a higher structural wall-to-floor area ratio that is structurally more rigid than the linear system. However, the compact arrangement of the spinal VB may lead to architectural design issues such as poor access of natural lighting, especially for the interior modules. Improvements can be made by separating closely packed modules into clusters, leading to the third massing typology, that is, cluster VB. Cluster type is widely adopted by the Singapore Housing and Development Board (HDB) in the design of public housing. Lastly, a centric VB layout suits well for smaller land size project in an urbanized area. The modules are radially arranged around the central core wall, forming a similar outlook as a typical high-rise building tower.[7]

Understanding the massing typology for VB could help to broadly decide on project requirements such as the number of story (N_{stry}), without detailed structural analysis. Figure 8 shows a massing typology plot of the 77 building blocks of the VB projects collected in the database. It was observed that linear VB was adopted mostly for low-rise VBs (less than 10 stories) lowering the need for core walls from a structural perspective. However, structural walls become more important for mid-rise VBs (10 to 25 stories), where spinal, cluster, and centric configurations are the viable choices. For high-rise VBs (more than 25 stories), centric and spinal forms are feasible. Readers are reminded to consider site constraints such as land plot size and geometry, which is crucial in choosing the suitable massing typology. This can be observed using the *x*-axis in Figure 8 for average gross floor area per story (GFA_{stry}), where a larger plot site is required for spinal form compared to centric, as it has a higher demand of GFA_{stry}. The definition of GFA_{stry} is illustrated in Figure 11c, which will be discussed in more detail later.

Despite numerous efforts to encourage full adoption of off-site prefabricated buildings,[42] VB exhibits different prefabrication levels across the four massing typologies. In this study, a prefabrication ratio (p) is introduced in Equation (1) to describe the level or scale of prefabrication.[43,44]

$$p = \frac{GFA_m}{GFA_{norm}}, \tag{1}$$

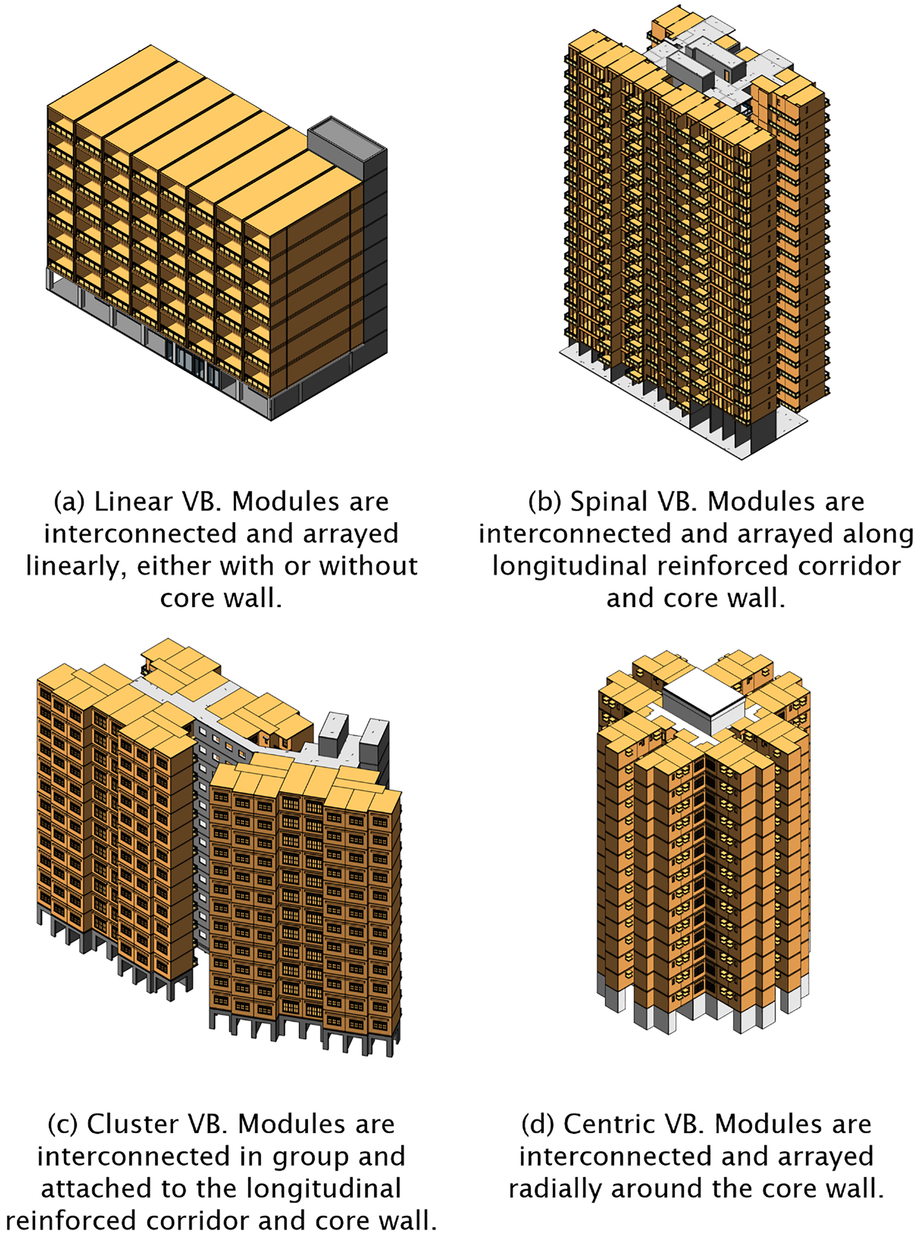

FIGURE 7 Generalized massing typologies of VB

where GFA_m is average gross floor area per module and GFA_{norm} is normalized gross floor area per module (refer to Figure 11d, which will be discussed in more detail later).

The prefabrication ratio is important to correlate the normalized gross floor area per module (GFA_{norm}) with average gross floor area per module (GFA_m) and account for the constructability of non-prefabricated structural system of VB. The magnitude of prefabrication ratio is formulated to range from zero to unity, where a full prefabrication is equal to unity. Figure 9 shows the postprocessed data of prefabrication ratio for the four VB massing typologies. The median of prefabrication ratio for linear VB is found to be 0.90, while others are approximately 0.75, which could be because in-situ shear or core walls are optional for linear VB systems. Interestingly, innovative construction techniques such as shotcreting of prefabricated shear wall construction[11,45] may achieve a higher prefabrication ratio for centrically configured VB systems. Most of the VB projects included in the database were constructed in regions of low-to-moderate seismicity, except for NA003 and NA007 to NA010 which were constructed in higher seismicity regions. It was discovered that the prefabrication ratio could be lower in these higher seismicity regions, given that more in situ concrete walls are needed as the lateral resisting structural components. For simplicity, the average prefabrication ratio of all massing typologies could be taken as 0.80 (i.e., an average of 80% with prefabricated modules and the remaining 20% to be constructed with nonprefabricated structural components).

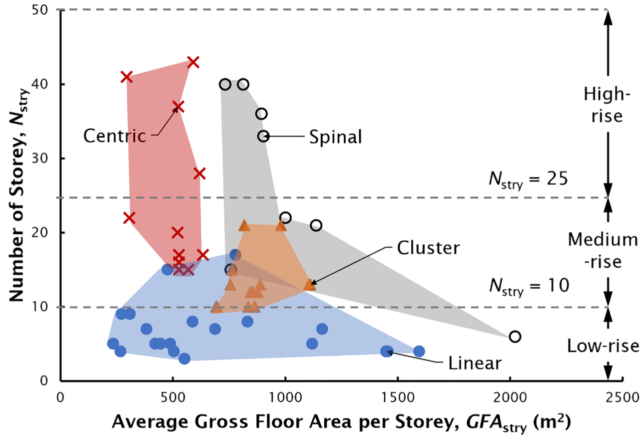

FIGURE 8 Distribution of database according to number of stories, average gross floor area per story and massing typologies

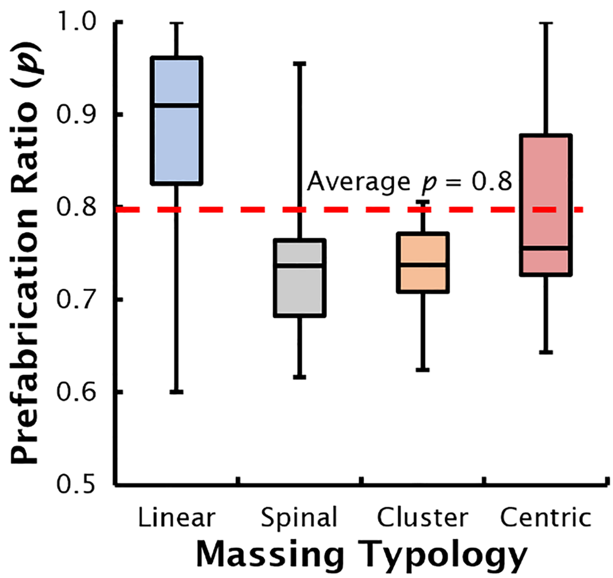

FIGURE 9 Prefabrication ratio of VB presented in box plots

4.3 | Development scale of VB project

A large-scale development project could achieve economies of scale and benefit from the use of VB. However, there is no available model to inform the stakeholders on the relationship between the development scale of VB project and the number of modules required. Hence, based on the collected VB database, a new empirical formula is proposed in Equation (2).

$$N_m = 15.7 GFA_{proj}^{\ 1.23}, \tag{2}$$

where N_m denotes the number of module and GFA_{proj} is the total gross floor area of the project, in unit of thousand square meter (10^3 m^2). Readers are advised to refer to Figure 11a for illustration of GFA_{proj}.

The detailed data for deriving Equation (2) is presented in Figure 10, with a strong correlation is observed. It is found that the module size reduces as the development scale of VB project expands, likely due to transportation cost and construction speed. For small-scale VB development, minimization of transportation trip for modules may be the top priority in VB design.[20] Thus, a lesser quantity but larger in size module is generally the preferred solution. Nonetheless, consideration of construction speed is progressively overshadowing transportation cost as the development scale of VB project increases. Goh and Goh[1] claimed that lifting efficiency is greatly improved for smaller modules than a larger

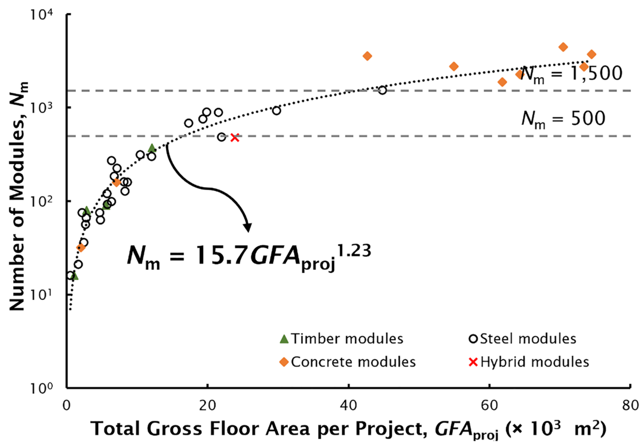

FIGURE 10 Proposed empirical equation to estimate number of modules based on total gross floor area per project

module. Hence, the mass production of smaller modules is more favorable in VB design for large-scale development, evidently based on the collected database.

Figure 10 also shows the choice of module materials is closely related to the required number of modules. Two threshold lines were identified at 500 units and 1,500 units of modules. The selection of module construction material has wider options for module quantity lesser than 500 units. Apart from conventional materials (steel and concrete), innovative materials such as engineered timber and composite material were adopted in some small-scale VB pilot projects. However, conventional materials become favorable, where steel module is used for 500 to 1,500 units of modules and concrete module is applied for larger VB development with N_m more than 1,500 units. The choice of material based on the data may have implicitly embedded factors such as site proximity to transportation linkage or logistic centers for the projects. Nevertheless, the preliminary suggestions are guidelines and not rigid decisions, where the users of the tool can refine the designs after a detailed site analysis

5 | PROPOSED DESIGN TOOL FOR VB

The proposed design tool is formulated by consolidating four VB design parameters at different hierarchical levels discussed in the previous section, namely, (i) total gross floor area per project (GFA_{proj}), (ii) average gross floor area per building (GFA_{bldg}), (iii) average gross floor area per story (GFA_{stry}) and (iv) normalized gross floor area per module (GFA_{norm}). For clarity, these design parameters are graphically shown in Figure 11 (a) to 11(d). Readers are cautioned that the measured gross floor area in the database consists of the entire floor area, including some minor openings.

5.1 | Basis of the four quadrants of the proposed design tool

The design tool can be presented in four graphs according to the hierarchical levels. However, it is devised into a four-quadrant plot by consolidating the four VB design parameters, which is schematically illustrated in Figure 12 to facilitate the explanation of the theoretical basis of the framework. The quadrants are arranged in sequence of Q1 to Q4, sweeping from top left to bottom left (counter-clockwise for Q1 to Q2) and then top right to bottom right (clockwise for Q3 to Q4). Each quadrant consists of four components of information, that is, axis, slope, slice, and shaded region. This information embeds the results of (i) various GFAs, (ii) number of tower blocks required, (iii) number of stories, (iv) massing typology, (v) module quantity, (vi) module dimension and (vii) module material.

The axes represent the four VB design parameters, which are the gross floor area (GFA) at different hierarchical levels. The theoretical basis of the relationship between the GFAs is expressed by a linear function of $y = mx$, where x and y-axes represent GFAs at different hierarchical levels, and m is the slope which is the controlling parameter in the quadrant. For example, the total GFA of a project is the number of VB towers multiplied by the GFA of a single VB tower, followed by the total GFA of a single VB tower is the number of stories multiplied by the GFA of a single story (more detailed explanations are presented later in this sub-section according to quadrants). Regions (shaded and non-shaded) within a quadrant that are separated by slopes are known as slices. The shaded area is formulated based on the feasible envelope of VB projects collected in the database.

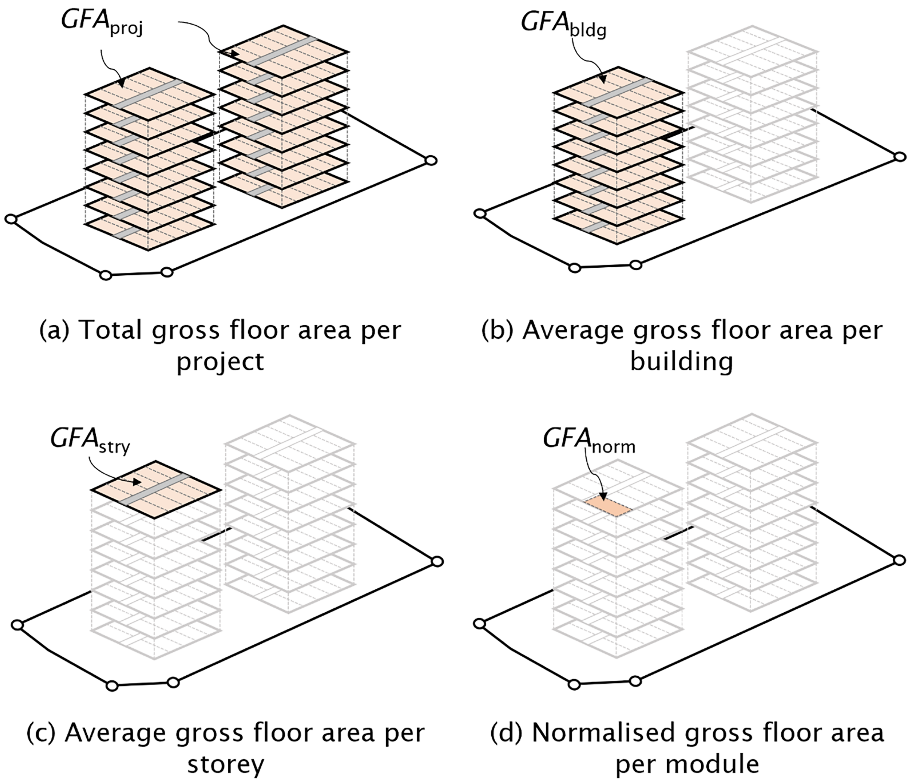

FIGURE 11 Illustration of the four design parameters

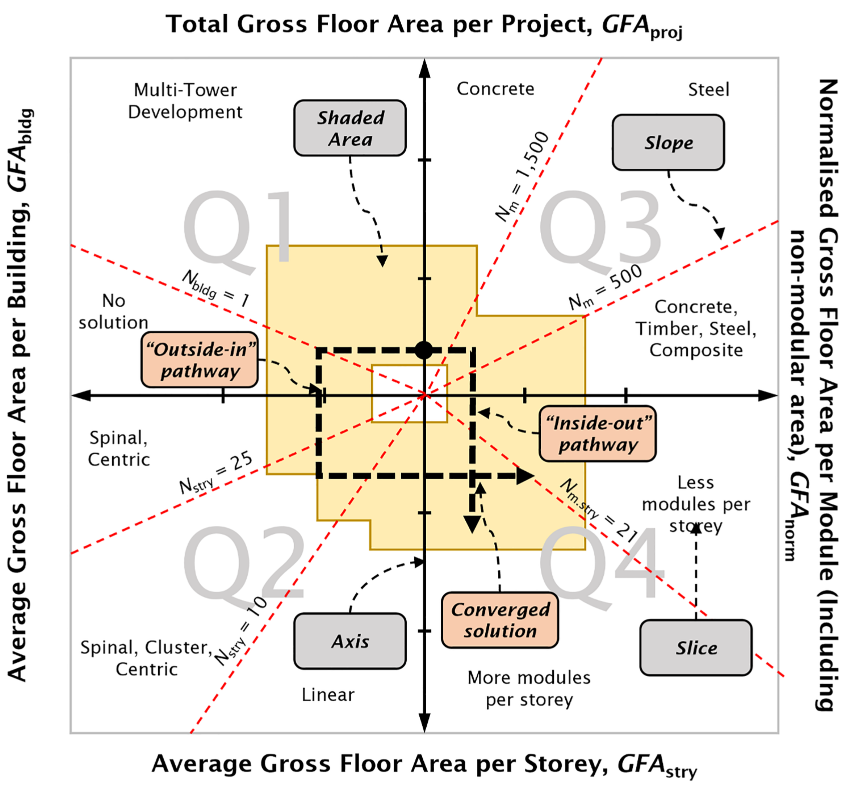

FIGURE 12 Schematic illustration of the four-quadrant plot of the proposed design tool

5.1.1 | Quadrant 1 (Q1)

The first quadrant of the proposed design tool describes the relationship of the GFA of a project and a building, as defined in Equation (3).

$$GFA_{\text{proj}} = N_{\text{bldg}} \times GFA_{\text{bldg}} \tag{3}$$

where N_{bldg} is the number of VB within a project, which is the slope in Q1.

A project that consists of only one tower block ($N_{\text{bldg}} = 1$) is referenced to show the solution for multi-tower development in the upper slice (it should be noted that the lower slice is invalid as there is no solution for VB design that consists of N_{bldg} less than one). Although highly repeatable VB design is encouraged in the literature to increase module production efficiency, it does not stop the designer from adopting different VB designs for each building in a multi-tower development project.

5.1.2 | Quadrant 2 (Q2)

Following a counter-clockwise direction from Q1, Q2 is the relationship of the GFA of a building and a story. The relationship is defined in Equation (4).

$$GFA_{\text{bldg}} = N_{\text{stry}} \times GFA_{\text{stry}} \tag{4}$$

where N_{stry} is the number of stories of a VB, which is the slope in Q2.

It is noted that Q2 is inter-related with Figure 8, where the selection of massing typology is carried out. The N_{stry} thresholds for low-rise, medium-rise and high-rise VB are 10 and 25, which are the slopes in the plot, producing three slices, that is, linear form at the lower slice; spinal, cluster and centric forms at the intermediate slice; and spinal and centric forms at the upper slice.

5.1.3 | Quadrant 3 (Q3)

Q3 is "reset" to start at the top right quadrant and not following through counter-clockwise direction after Q2. The GFA relationship of a project and module is formulated in Equation (5).

$$GFA_{\text{proj}} = N_{\text{m}} \times GFA_{\text{norm}} \tag{5}$$

where N_{m} is the number of modules, which is the slope in Q3.

Importantly, users are reminded that GFA_{norm} is not equivalent to GFA_{m}, but they are relatable by prefabrication ratio (p) in Equation (1). In this quadrant, the controlling parameters are the thresholds N_{m} presented in Figure 10, that is, reference N_{m} at 500 units and 1500 units. Hence, as explained in Figure 10, similar findings are presented in Figure 12, where the lower slice with N_{m} lesser than 500 units are modules constructed with more choices of materials (concrete, timber, steel, and composite). The intermediate and upper slices exhibit the dominance of steel and concrete, respectively.

5.1.4 | Quadrant 4 (Q4)

The final Q4 (clockwise from Q3) is associated with GFA relationship of a story and a module, which is formulated in Equation (6).

$$GFA_{\text{stry}} = N_{\text{m.stry}} \times GFA_{\text{norm}}, \tag{6}$$

where $N_{\text{m.stry}}$ is the number of module per story, which is the slope in Q4.

A reference $N_{\text{m.stry}}$ is fixed at 21 units, as per the global median value compiled from the collected database. VB with $N_{\text{m.stry}}$ exceeding 21 is considered more than the norm (represented by the lower slice), and vice versa, less than the norm (represented by the upper slice).

5.2 | Feasible envelopes across regional groups

The feasible envelopes are compiled from the database and illustrated as shaded areas in Figure 13, superimposed on the proposed design tool. These feasible envelopes are the "solutions" based on past projects (assuming that the "desire path" philosophy is applicable). The envelopes were found to be regional-dependent rather than having a generic global boundary. This is evidently shown in Figure 13a–d, for regional groups of AS, EU, NA, and OC, respectively. The shapes of the envelopes are distinctively different for the regional groups, except for NA (i.e., Canada and the United States) and OC (i.e., Australia), which shared some similarities. It is noted that the existing VB design collected in the database is the result of multiple PEST factors. Although these PEST factors vary across countries, a relatively similar PEST environment is expected among neighboring countries within a regional group. Hence, feasible envelopes are categorized by regional groups to reveal regional VB design practice.

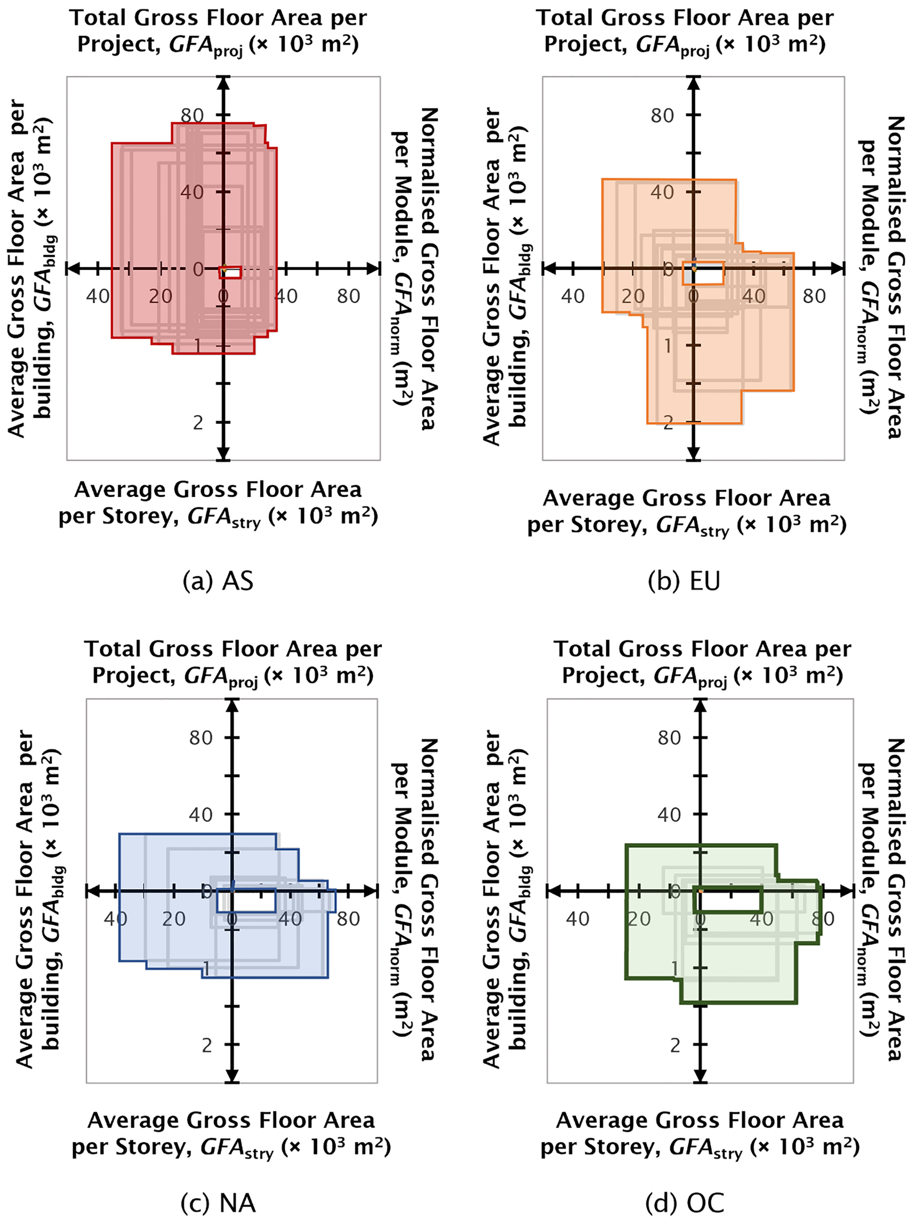

FIGURE 13 Feasible design envelops of each regional group *Notes*: Grey lines are the plot based on projects in collected database

5.2.1 | VB design in regional group AS (Hong Kong, Malaysia, Singapore)

In regional group AS, a VB project is typically associated with multiple tower blocks of mid-to high-rise VBs (i.e., GFA_{proj}/GFA_{bldg} is greater than one). The development scale is often large, with GFA_{proj} marked at about 70,000 m^2. Large-scale design is a result of government intervention in policy and financial support. For instance, the adoption of PPVC is mandated in Singapore for land parcels awarded under Government Land Sales (GLS) program since 2014.[17] Hence, various VB massing typologies, except linear form, are commonly adopted in regional group AS. Conventional construction materials such as steel and concrete are dominant because of the larger module quantity required.

5.2.2 | VB design in regional group EU (France, Germany, Spain, and United Kingdom)

In regional group EU, VB projects are typically single block low-rise buildings, with very few high-rise buildings. It is noted that majority of the VB projects in regional group EU are privately funded, which led to smaller VB development scale (e.g., GFA_{proj} of approximately 40,000 m^2). Although the project scale is smaller than that in regional group AS, the average GFA_{stry} is higher, probably due to the wider plan area per story. Linear form massing typology is commonly adopted for low-rise, while centric form is preferred for mid- and high-rise VB. It appears that the choice of module construction material is open to various options, as most of the VB projects require less than 500 units of modules per project.

5.2.3 | VB design in regional group NA (Canada and the United States)

The feasible envelope for regional group NA is squatter in geometry compared to the previous regional groups (AS and EU). In regional group NA, the development scale of VB project is generally smaller, with a maximum GFA_{proj} of approximately 30,000 m^2. The majority of VB projects in regional group NA are low-rise single block building. However, there is also one high-rise VB (i.e., the 33-story Atlantic Yards B2[46]). All massing typologies, except for cluster form, were adopted. The lower demand on the number of modules (N_m) led to the use of engineered timber and steel module.

5.2.4 | VB design in regional group OC (Australia)

Regional group OC has a squat envelope, very similar to regional group NA. The development scale is generally small (GFA_{proj} of approximately 25,000 m^2) and it is weighted towards a single tower block design ($N_{bldg} = 1$). Historically, VBs in regional group OC were low-rise; hence the massing typology has shown a linear form. A few high-rise VBs with spinal and centric forms were recently constructed.[11,24] For module construction material, steel is the most common option in regional group OC.

5.3 | Procedure of using the proposed design tool

A VB design process is different from that of a conventional cast in-situ reinforced concrete building or steel building, as it has additional considerations in prefabrication. "Inside-out" design was proposed by Hayes,[14] where the design process of VB should start from module level to global structure because module design is often governed by transportation restriction and logistic planning. Meanwhile, an "outside-in" design is not commonly discussed in the literature, where a VB can be designed by setting a set of global target parameters, such as the number of tower blocks (N_{bldg}), massing typology and then progressively sizing up the module design. A hybrid framework is adopted in the proposed design tool, where a converged solution is obtained from the intersection of an "outside-in" pathway (counter-clockwise from Q1 to Q2 in Figure 12) and an "inside-out" pathway (clockwise from Q3 to Q4 in Figure 12).

The proposed procedure is further illustrated in a flow chart in Figure 14, with six key steps procedure. In Step 1, GFA_{proj} is the first to be established to initiate the preliminary design of VB. GFA_{proj} is often predetermined in the client's requirement. In circumstances where the GFA_{proj} is uncertain, especially in VB pilot project, the feasibility envelope could be adopted as a starting point to determine a reasonable value of GFA_{proj}. In Step 2, GFA_{bldg} is determined based on the selected N_{bldg} (either single or multiple tower blocks). In Step 3, based on a desired number of stories of each tower block (N_{stry}), GFA_{stry} and its suitable massing typology could be easily identified. Readers are reminded to comply to any relevant local building code, for example, height constraint and permissible floor area ratio (FAR) of the project site, consider local construction industry and site constraints when determining the number of stories of each tower block (N_{stry}). In Step 4, determine the required number of module (N_m). Equation (2) can be used to estimate the approximate N_m based on the predetermined GFA_{proj} in Step 1. Concurrently, GFA_{norm} and module material are identified. In Step 5, the average number of modules per story ($N_{m.stry}$) is automatically determined from the intersection of GFA_{stry}

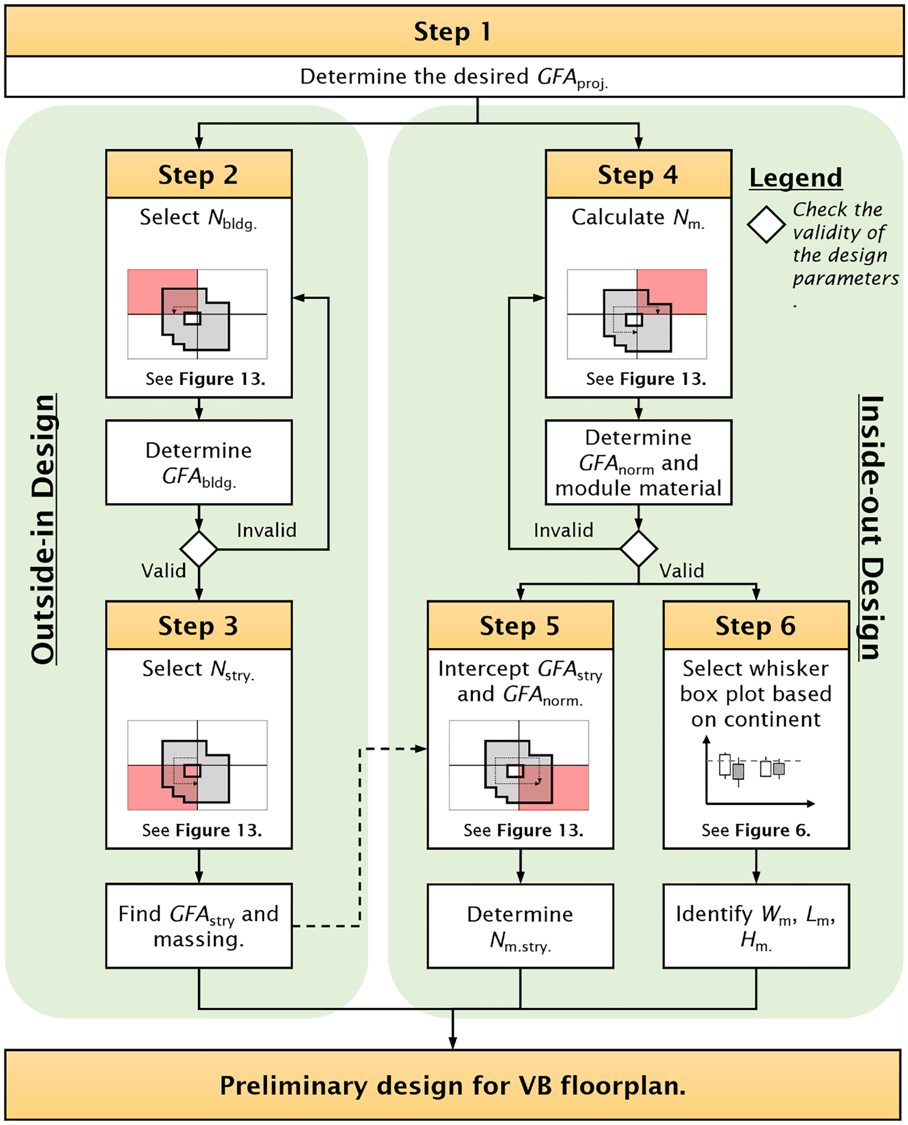

FIGURE 14 Proposed procedure of using the design tool

and GFA_{norm} in Q4 of the design tool. In Step 6, compute the targeted GFA_m from the determined GFA_{norm} using Equation (1), with a prefabrication ratio (p) based on Figure 9. Once a GFA_m is determined, the designer can select a suitable dimension of the module using Figure 6.

5.4 | Design tool programmed in spreadsheet

A spreadsheet is programmed according to the proposed design tool for the convenience of VB designers and developers. Readers can also duplicate the proposed design tool framework using other programming platforms. This spreadsheet is made public, and the link is provided in the Supporting Information. An example of its user interface is shown in Figure 15. The architecture of the interface is divided into four sections, which include data input, data processing and visualization, design tool recommendation, and graphical user interface (GUI) setting.

For data input in Sections A and B, users are requested to input the intended total gross floor area per project (GFA_{proj}) and the controlling parameters of the designed VB into the input cell, as shown in Figure 15. Sections A and B are Steps 1 to 5 of the design tool framework shown in Figure 14. The user can perform iteration and refinement based on the comments and feedback provided by the program.

For data processing and visualization in Section C, the input is further processed and computed for the design parameters using Equations (3)–(6). The computed results are superimposed with the feasible envelope based on the selected VB database for visual comparison.

For design tool recommendation in Sections D to F, the summary of the VB design parameter and design tool recommendation for global and local VB design are provided. Global VB design details such as number of building (N_{bldg}), number of story (N_{stry}) and feasible massing typology

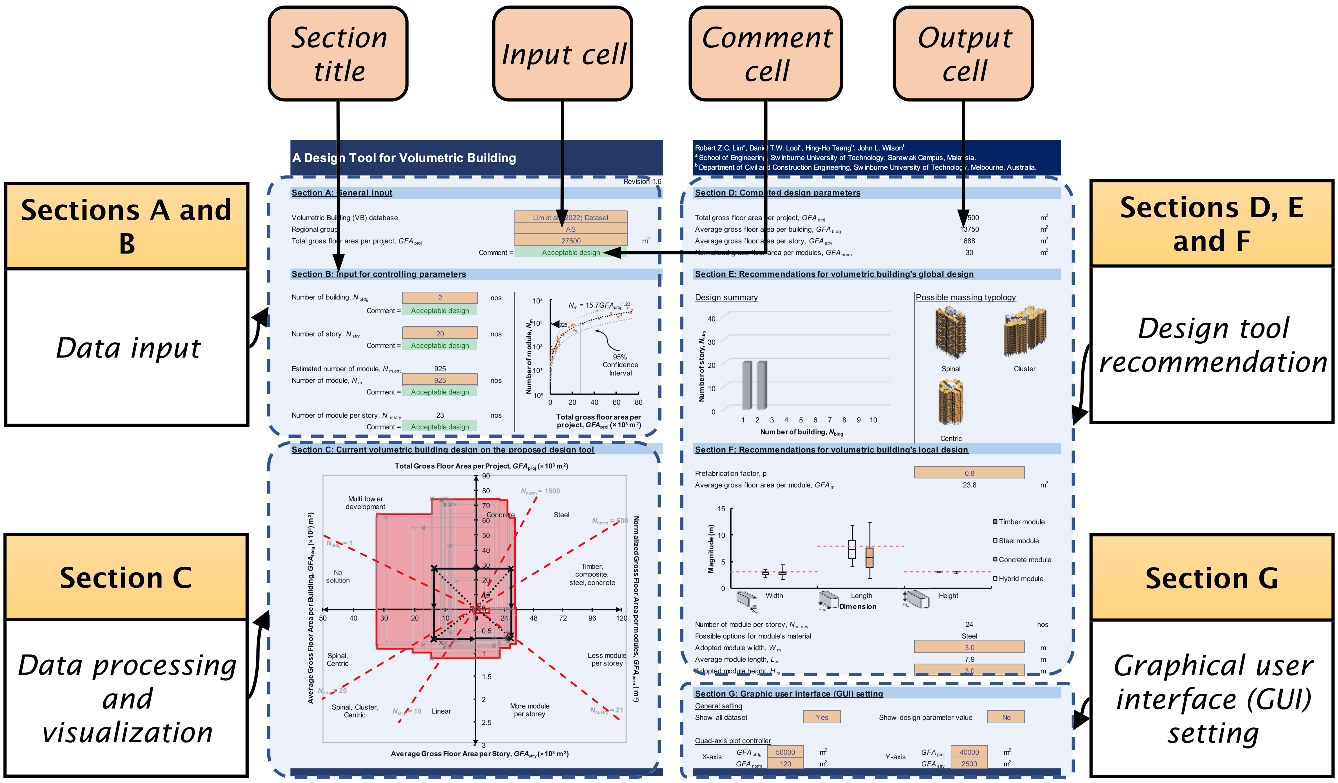

FIGURE 15 User interface of the developed design tool and its components

can be obtained in Section E. Section F allows iterations for VB local design based on the box plots, which is Step 6 of the design tool framework as shown in Figure 14.

The GUI setting in Section G provides users with an option to control the graphical settings of the four-quadrant plot. Any change applied to this section will not affect design tool recommendations.

6 | APPLICATION OF THE PROPOSED DESIGN TOOL: A CASE STUDY

A case study of an independent actual VB project (not included in the database) is presented in Figure 16 to provide validation using the design tool. The selected VB project is known as Ash Street Redevelopment in Hong Kong. The floor area ratio (FAR) is about 8, with the site area and GFA_{proj} of 420 m^2 and 3,340 m^2, respectively. Figure 16(a) shows an exploded view of the VB layout. The design features a 23-story centric VB, with a GFA_{stry} of about 145 m^2. It has two room types (single and double bedroom units), constructed with 161 units of the concrete module (i.e., seven modules per story). The actual module width, W_m is between 2.4 and 2.8 m with an average of 2.6 m. For the actual module length, it has an average value of 5.0 m. The module height was capped at 3.2 m, fulfilling the local transportation and architectural requirements. The pre-fabrication ratio is about 0.63.

Based on the parameters of the actual project, the information is fed into the design tool for validation purposes. Given a small site area, only one building is feasible for this project. The height of the module is fixed at 3.2 m. The first simulation (Design Alternative A, shown in Figure 16b) is done for concrete module, which resulted in a similar average GFA_{stry}, with an average width of 2.5 m. The median prefabrication ratio of 0.75 for centric VB (refer to Figure 9) was assumed, resulted in an increase of GFA_m. The final recommendation is a smaller core wall region (but still fulfilling the requirement of lift services and staircase) with a longer concrete module design (i.e., the average module length, L_m had increased from 5.0 to 6.2 m).

The second simulation (Design Alternative B) is presented in Figure 16c to demonstrate the application of the design tool for a situation targeting for minimum numbers of modules and stories. The outcome of the design based on the feasible envelope of regional group AS, is a centric 17-story VB with 102 units of steel modules. Assuming a prefabrication ratio of 0.75, the required average module length increased to 9.8 m and steel module is a more viable option than the concrete module to achieve a longer span. The final recommendation has a larger core wall region with longer module spans across room types.

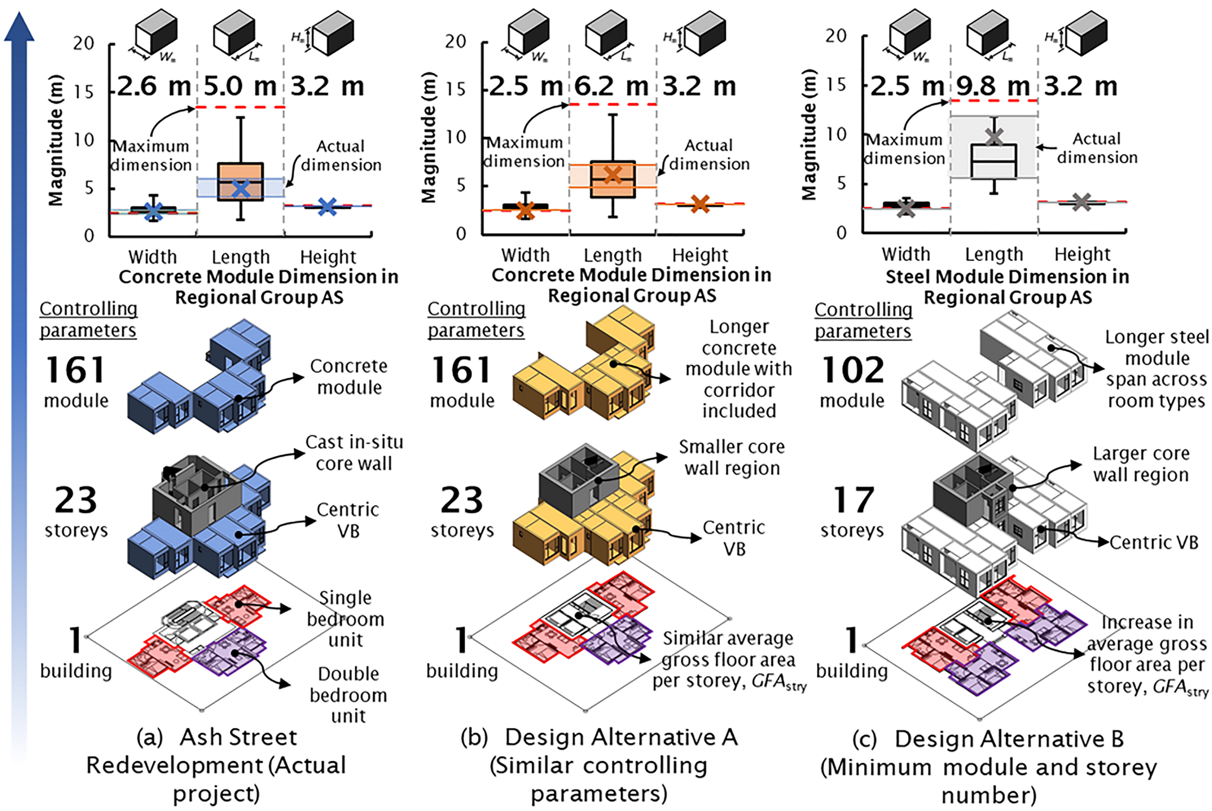

FIGURE 16 Comparison between the VB design of actual project and design alternatives for Ash Street Redevelopment

The design tool can simulate two solutions, that is, Design Alternatives A and B. However, the designers must consider external criteria such as site limitation, geographical location and logistics. Given the situation is in Hong Kong, transporting a 9.8 m module can be challenging at narrow and hilly roads conditions in the city. Hence, Design Alternative A seems to be the solution, which validated the use of concrete modules with the exact number of module predicted, with slight difference in module length and prefabrication ratio.

7 | CONCLUSIONS

This paper presented a unified concept of carrying out the preliminary design of VB, which is the first of its kind in the literature. The proposed design tool helps the stakeholders to estimate the number of modules, size of modules, choice of massing typology and module construction material. The extensive VB database collected in this work is precious for researchers, as no such database is available. Besides the framework, one of the contributions of this work is the new empirical model in Equation (2), which shows a strong correlation between the number of modules (N_m) and the total gross floor area per project (GFA_{proj}). Although the design tool has considered many essential parameters, it cannot consider some external parameters. Hence, users are reminded to consider other constraints such as local building code, site and construction constraints during preliminary VB design. Also, the design tool is formulated based on the collected database (sourced until July 2021) with the assumption of the "desire path" philosophy. Nonetheless, users can customize the database in the spreadsheet developed by the authors to allow for the inclusion of new projects, forming another feasible design envelope. After implementing the tools, feedback and comments from the users would be an interesting topic to share with the building communities in the future. The design tool could be further optimized by integrating artificial intelligence approaches such as machine learning and deep learning as a future outlook in volumetric building research.

ACKNOWLEDGMENT

The work in this article was supported by the Fundamental Research Grant Scheme of the Malaysia Ministry of Higher Education (FRGS/1/2021/TK01/SWIN/02/1). Open access publishing facilitated by Swinburne University of Technology, as part of the Wiley - Swinburne University of Technology agreement via the Council of Australian University Librarians.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

NOMENCLATURE

GFA_{bldg}	average gross floor area per building
GFA_{m}	average gross floor area per module
GFA_{norm}	normalized gross floor area per module
GFA_{proj}	total gross floor area per project
GFA_{stry}	average gross floor area per story
H_{m}	module height
L_{m}	module length
N_{bldg}	number of building
N_{m}	number of module
$N_{m.stry}$	number of module per story
N_{stry}	number of story
p	prefabrication ratio
W_{m}	module width

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

How to cite this article: R. Z. C. Lim, D. T. W. Looi, H.-H. Tsang, J. L. Wilson, *Struct Design Tall Spec Build* **2022**, *31*(13), e1946. https://doi.org/10.1002/tal.1946