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Towards dynamic vertical urbanism: A novel conceptual framework to develop vertical city based on construction automation, open building principles, and industrialized prefabrication

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ABSTRACT

Nowadays a great number of new developments are claimed in the name of "vertical city", yet few represent this important characteristic. This paper aims to propose a novel vertical city framework, or in other words, dynamic vertical urbanism, featuring constant vertical urban transformation by applying the state-of-the-art construction technologies. First, successful and unsuccessful precedents of building complexes which inspire this novel concept will be analyzed. In addition, building technologies that are crucial for the implementation of this framework will be introduced. As a result, this vertical city concept has the ability to integrate five basic elements of a city: vertical and horizontal circulation systems as its paths, a flexible building envelope as its edges, variable mix-used functional blocks as its districts, sky bridges and roof gardens as its nodes, and the complex itself as a landmark. More importantly, it can change its size, form and function with the help of construction automation technologies, open building principles, and process information modeling. it can also responsively evolve in accordance with social, economic, and environmental shifts in a self-sufficient manner, meanwhile avoiding the risk of being homogeneous with surrounding buildings. Finally, the complex will perform as a series of interconnected components which act together to form a living organism that provides various functions such as corporate, residential, commercial, academic, medical, legal, and infrastructural. In conclusion, this paper will provide researchers, architects and urban designers with a valuable example for the future vertical city developments and beyond.

KEYWORDS

Dynamic vertical urbanism, Modularization, On-site construction factory, Process information modeling, Vertical city

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Introduction

A city is a sophisticated organism which is constantly changing throughout its lifecycle, as a result of economic shifts, demographic change, and environmental pressures. Nowadays, megacities in China are facing unprecedented issues such as overpopulation, population aging, land shortage, ghost cities, and environmental pressures during the process of uncontrollable urban sprawl [1,2]. Meanwhile, a considerable number of new developments claim themselves in the title of "vertical city", yet very few represent the essence of a city. The definition of vertical city cannot be solely judged by its height, usage, or investment return, but has to demonstrate the capability of adaption in response to urban transformation. This paper aims to explore a novel framework of vertical city, or in other words, dynamic vertical urbanism, featuring constant vertical urban transformation through applying the state-of-the-art construction technologies preliminarily in the context of megacities in China. Meanwhile, this vertical city approach has the ability to integrate city's basic elements such as paths, edges, districts, and landmarks [3]. More importantly, it can change its size, form and function with the help of construction automation technologies and Open Building principles. It can also responsively evolve in accordance with social, economic, and environmental shifts in a self-sufficient manner, meanwhile avoiding homogenization with surrounding buildings. Eventually, the complex will perform as a series of interconnected components which act together to form a living organism that performs a variety of functions and purposes.

Background and literature review

In this section, the current situation and research gap of vertical city are concisely described. Furthermore, building complexes in different cities with various destinies are demonstrated, which inspire the dynamic vertical urbanism approach. In addition, urban design theories and building technologies that are crucial for the implementation of this approach will be introduced.

"Vertical city": The research gap

Today, the concept of "vertical city", a type of terminology that has never been strictly articulated, is becoming more and more popular [4]. Many cities around the globe are enthusiastically adopting tall buildings in the name of vertical city as one of the main building typologies [5]. Multiple factors fostered the rise of the vertical city concepts and practice. Researchers identified several key factors that catalyzed the generation of vertical city concepts: (1) rapid population growth especially in urban areas, (2) deteriorated ecological conditions in cities caused by overpopulation and urban sprawl, (3) the urgent need for sustainable development, (4) urban residents' desire to lead a comfortable lifestyle, and (5) severe land shortage in large cities [6]. Accumulated building technologies make it possible to build large urban complexes in a vertical manner, and a large number of new developments in East Asia, the Middle East, Europe, and Americas portray themselves as "vertical cities" [7–9]. However, few of them address one key essence of a city, which is the ability to continuously grow and transform in terms of forms and functions.

Learning from St. Louis, Tokyo, Cairo, and Chicago

Oftentimes a building will face an unpleasant destiny when it reaches the end of its lifecycle, which is demolition. Designed by renowned architect Minoru Yamasaki, Pruitt-Igoe, St. Louis is arguably the most infamous failure of American social housing projects. Largely due to issues such as insufficient building quality, homogeneous design of each building, lack of functional flexibility, poor maintenance, occupancy rate decline, poverty, crime, and racial segregation, the over-scale complex of 33 buildings were demolished with explosives in 1972, which later became a symbolic event of unreasonable planning and waste of construction resources [10]. Presumably, Pruitt-Igoe might have a completely different fate if all these abovementioned issues were properly addressed (see Fig. 1).

Contrary to Pruitt-Igoe, however, a silver lining can be found in the influential Metabolist movement in Japan. Let us take a glance at two notable buildings in Tokyo created during the Metabolism movement.

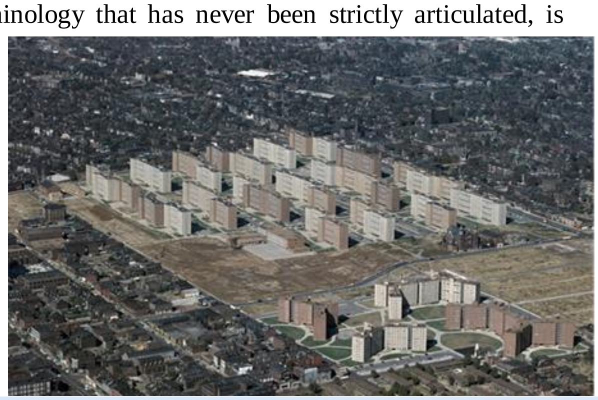

Figure 1. Aerial views of the Pruitt-Igoe complex before and after the explosion. Left: United States Geological Survey (Public Domain); right: U.S. Department of Housing and Urban Development (Public Domain)

The first one is the Nakagin Capsule Tower which was designed by Kisho Kurokawa and completed in 1972. As the world's first capsule architecture put into use, it is considered revolutionary for its futuristic appearance, modularized design, and factory-produced living units. After Japan's economic bubble burst in early 1990's, the building's fate began to turn grim. Due to lack of funds, the interior of the building fell into disrepair [11]. Finally, it was reported in 2007 that the association of tenants at the Nakagin Capsule Tower voted to demolish this historic landmark because of the use of asbestos in the capsules, the concerns of its ability to withstand earthquakes, and more importantly, its inefficient use of land [11,12]. Another example worth noting is the Fuji TV Building designed by Kenzo Tange (see Figure 3). Besides the magnificent spherical observation platform, one of the most eye-catching highlights of the building is three pairs of enclosed pedestrian sky bridges connecting the media and office towers, which create a considerable amount of flexibility and mobility for its occupants [13]. Being a large futuristic multifunctional complex, however, the main function of this tower as a whole was mostly fixed since its erection in 1997, which is the headquarters of Fuji Television Network.

By observing these two signature projects of the Metabolist movement in Tokyo, it is obvious that they opened a whole new door in the field of architectural design for their industrialized modularity and interconnectivity. However, they both are far from been considered as "vertical cities" due to abovementioned reasons. Admittedly, they broke fresh ground in the history of architecture, but their functions and volumes are still not able to evolve in accordance with social, economic, and environmental changes.

Figure 2. Nakagin Capsule Tower in Tokyo, Japan. Photo By Jordy Meow (unchanged and licensed under CC BY-SA 3.0, https://creativecommons.org/licenses/by-sa/3.0/)

Figure 3. Fuji TV Building in Tokyo, Japan. Photo by Kakidai (unchanged and licensed under CC BY-SA 4.0, https://creativecommons.org/licenses/by-sa/4.0/)

To answer the question that Metabolism did not clearly answered, we can find some inspiration from Cairo's urban slums. Cairo, the capital city of Egypt, is arguably the largest metropolis in Africa, and one of the largest in the world. Today, around two-thirds of Greater Cairo Region's 20 million residents live in urban informal settlements (see Figure 4). Even though various issues such as overpopulation, high unemployment rate, land shortage, poor living conditions, inadequate infrastructures, and environmental challenges exist in these informal settlements, they still manage to achieve self-sufficiency and maintain a strong community through their seemingly chaotic, but flexible structural system, which can be continuously extended vertically (and in some cases even horizontally) [14].

Figure 4. An aerial view of Cairo's informal urban settlements. Photo by Silar (unchanged and licensed under CC BY-SA 3.0, https://creativecommons.org/licenses/by-sa/3.0/)

In the research project A2L-Mobilius (funded by the Germany Ministry for Education and Research, Grant Number: GERF-IB-033 Almobilius_01DH14003), inspired by Cairo's informal communities, researchers developed an affordable and adaptable building system (A²BS) to help to gradually transform the informal settlements. As shown in Figure 5, the system is based on the principle of Open Building concepts, which consist of three sub-systems that can be easily prefabricated by local residents: the modular structural sub-system, the building envelope sub-system, and the service infill sub-system. The structure itself can be extended vertically and horizontally with newly built, structural elements in order to achieve maximum flexibility and to allow the building to evolve over time [15].

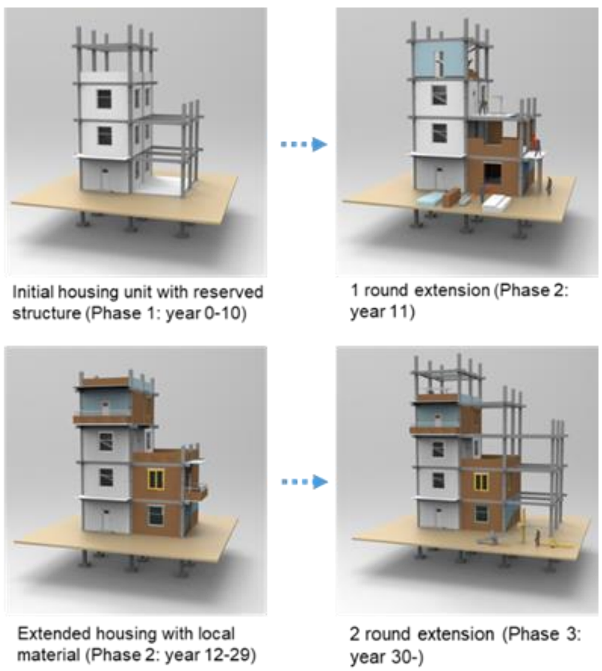

Figure 5. An evolutionary development scenario of A²BS Building System

A similar approach also can be observed in the design and construction process of large modern commercial buildings. For instance, Blue Cross Blue Shield Tower in Chicago, Illinois, is a 57-story, two-phased, vertically expanded office tower. The building's 33-story first phase was completed in 1997, and more than 10 years later in 2010, phase two was completed, adding 24 stories on top of the original, fully occupied building. During the expansion process, occupation in the lower original building remains normal and uninterrupted [16]. This example shows that through the innovative concept of vertical expansion, a building can successfully plan for a long-term growth without relocation, thus providing an excellent reference for the future expansion of vertical city (see Figure 6).

Figure 6. Blue Cross Blue Shield Tower in Chicago during expansion. Photo by Photogal (unchanged and licensed under CC BY-SA 3.0, https://creativecommons.org/licenses/by-sa/3.0/)

Review of theories and technologies to be applied in the novel vertical city

In order to achieve perpetual vertical urban transformation, there are several interconnected concepts and technologies which will serve as the core pillars of dynamic vertical urbanism (see Figure 7). These concepts and technologies will be analyzed in the following sections.

Figure 7. Six pillars in the novel vertical city framework

Five city elements

In the book, The Image of the City (1960), Lynch concluded that people formed mental maps of the surrounding urban area through five tangible elements: paths, edges, districts, nodes, and landmarks [3]. Accordingly, in order to achieve the authenticity of a vertical city, these five elements must be interpreted and reflected in the design process. Specifically, the novel vertical city has vertical and horizontal circulation systems as its paths, a flexible building envelope as its edges, variable mix-used functional blocks as its districts, sky bridges and roof gardens as its nodes, and the complex itself as a landmark.

Robot-oriented design

For many years, there has been a need of redesign of various construction tasks that are simple, repetitive and dangerous using ergonomic principles and automation technologies [17]. Therefore, Bock first initiated the concept of Robot-Oriented Design (ROD) in 1988, which emphasizes the idea that before the final on-site construction process, all parameters shall have been already considered at the earlier design and production stages. In order to establish determined conditions for robotic on-site operations, the elements of building sub-systems (e.g. building structure, component, assembly method, and equipment selection, etc.) need to be well defined geometrically and physically in accordance with robotics and automation [18].

Open building concepts

Open Building is a cross-disciplinary approach to the design of buildings that takes in account the possible need to change or adapt the building during its lifecycle, in accordance with social, economic, and technological changes. Open Building concepts gradually emerged in response to evolving social, political and commercial forces, to prevailing conditions and trends in residential construction, manufacturing and many other factors that demand more efficient and susceptive practices. The building is designed on different levels: support structure, infill system, fit-out and appliances [19,20]. Researchers have developed a number of Open Building systems on various levels [20–22]. All these levels have been updated and reinterpreted to utilize the benefits of state-of–the–art industrial production, emerging information technologies, improved logistics and changing social values and market structures. Apparently, buildings following Open Building principles will by no means become obsolete but will perpetually evolve in accordance with occupants' demands. Since its initiation, Open Building principles have been widely adopted by architects around the world in numerous projects, including the renowned NEXT21 in Japan and Molenvliet Project in Netherlands [23].

Modularization and industrialized prefabrication

Modularization and industrialized prefabrication play a significant role during the lifecycle of the novel vertical city approach. Usually several levels are defined in building prefabrication: lower-level components made of raw materials and parts (e.g. ceramic, brickwork, concrete, wood, steel, glass, polymers, etc.), mid-level building components (i.e. building sub-system manufacturing, such as kitchen modules, bathroom units, assistance modules, etc.), and high-level complete, prefabricated buildings [24,25]. In the novel vertical city approach, all main parts and components of the building will be prefabricated in factory while complying with Open Building concepts, in order to achieve flexibility and sustainability throughout the lifecycle of the vertical city.

On-site automation

Since the late 1980s, Japanese contractors began to realize that payoffs of single-task robots were limited unless more of the construction process could be automated and integrated. Therefore, they began to explore the application of manufacturing principles to construction [26]. There are four fundamental elements in an on-site automation system: (1) an on-site factory protected by an all-weather enclosure, (2) an automated jacking system, (3) an automated material conveying system, and (4) a centralized information control system. Most of the on-site construction factories use a just-in-time material delivery system, bar-coded parts or components, and a computerized information management system to improve the efficiency and quality of the construction process. Other tasks such as welding, painting, and concrete finishing can be further carried out by single-task construction robots. In addition, the on-site construction factory system can also be applied to the deconstruction process.

For example, Big Canopy, designed by Obayashi Corporation in 1995, was the first automated construction system applied to the construction of precast concrete structures. The Big Canopy itself is supported by at least four independent massive columns around the building, which allow more flexibility than other previous systems. In addition, the system has a synchronously self-climbing temporary roof, climbing devices, and overhead/jib cranes, all of which are supported by the massive columns. Once the floor is erected, the canopy is jacked up one story at a time and always left a two-story space in between the canopy and the on-site factory floor. Furthermore, the system has a parallel material delivery system which consists of overhead cranes and material delivery lifts (see Figure 8a) [27,28].

The HAT Down method, developed by Takenaka Corporation, is a closed sky factory supported by the building itself (i.e., moving downwards). The HAT Down system, which can be considered as a reversed on-site construction factory, consists of a series of integrated sub-systems: a sky factory roof structure; a descending system; a horizontal delivery system; lowering shafts; a material handling, sorting, and processing yard; a real-time monitoring and management system; and templates for cutting. In addition, a deconstruction site requires some novel types of end-effectors, such as a material sorting device for recycling, water-cutting, and laser-cutting (see Figure 8b) [28].

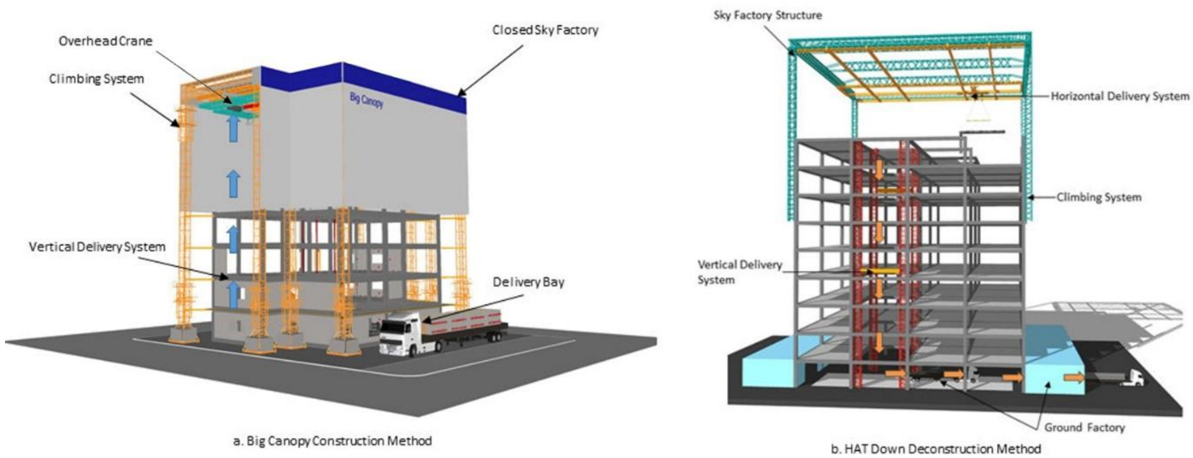

Figure 8. On-site automation sites. Top: Big Canopy Construction Method by Obayashi Corporation; bottom: HAT Down Deconstruction Method by Takenaka Corporation

Building information modeling

It is widely known that project management, which is the subject of coordinating different projects and keeping them on track within limited time, cost and resource, helps to create better plans, schedules, and profit [29]. To carry out an ambitious concept, an integrated project management framework that offers seamless, real-time data accumulation, processing, and distribution is required. In addition, the proposed management framework will cover design, manufacturing, logistics, on-site assembly, and lifecycle management phases of the tall building construction project. In this case, in order to manage a large amount of heterogeneous data from the physical and digital surrounding, only understanding the real word condition through knowledge-based and/or object-oriented technologies such as traditional building information modeling (BIM) application is insufficient. In addition, when implementing automation and robotic construction technology in the construction process, a know-how based, interactive, proactive and responsive version of BIM is required [30].

Results

Based on the analyses in the previous sections, a comprehensive approach is proposed to develop the vertical city with the concept of dynamic vertical urbanism. First of all, the proposed type of building complex is not supposed to be constructed in the congested urban centers, but in suburban areas near congested metropolises, serving as a self-sufficient satellite-type "vertical city" to support the most populated urban areas through rapid transit. Specifically, the novel vertical city complex has vertical and horizontal circulation systems as its paths, a flexible building envelope as its edges, variable mix-used functional blocks as its districts, sky bridges and roof gardens as its nodes, and the complex itself as a landmark.

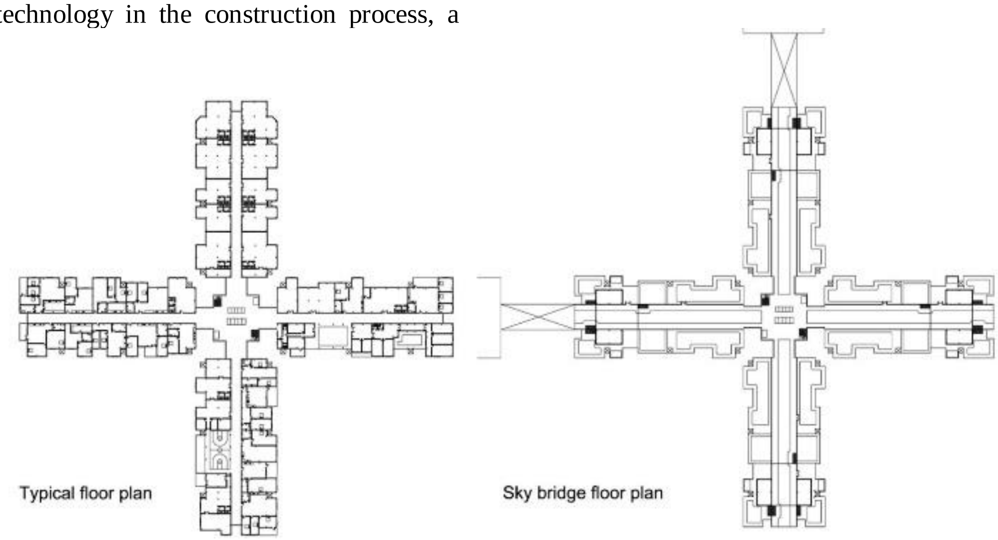

Figure 9. Typical floor plans in the dynamic vertical urbanism complex

Figure 10. An exemplary section of the dynamic vertical urbanism complex

Furthermore, each tower is overstructured to enable continuous expansion to a certain extend. It is worth mentioning that the proposed design complies with the design principles of sustainable skyscrapers concluded by Wood [31], including variation with height, new programs, communal spaces, envelope opacity, sky bridges and integrated vegetation. In addition, the research also closely follows the Roadmap on the Future Research Needs of Tall Buildings formulated by Council on Tall Buildings and Urban Habitat (CTBUH) [32]. The detailed concept is described and explained as follows.

Design overview

The proposed design demonstrates a type of floor plan that is commonly seen in China's construction industry (see Figure 9). There are four wings allocated around the central core structure. In order to maintain efficiency, each wing consists of maximum ten units (whether they are residential or office), which can be flexibly used for residential, commercial, office, and public purposes (e.g. school, hospital, police station, infrastructure, etc.) depending on the requirements of the stakeholders (see Figure 10). There are dedicated void spaces reserved on either side of the wing where the massive column structures for the self-climbing systems of the on-site factories are located (see Figure 11).

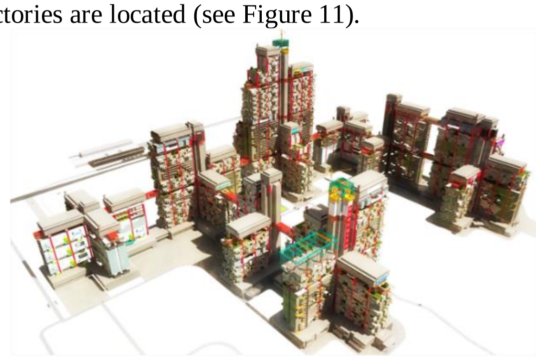

Figure 11. Aerial view of the proposed complex following dynamic vertical urbanism principles

On-site construction factory

In order to reduce the effects of the harsh surroundings on the robot performance as well as to provide a clean, quiet and unobtrusive jobsite environment to enable early and continuous occupation of the residents, it is critical to adopt automated construction factories [33]. On-site construction factories (OCF), which consists of the sky construction factory (SCF) and the ground construction factory (GCF), play a crucial role in the development of dynamic vertical urbanism (see Figure 12). With the help of the industrialized building design and the utilization of automation technology, the proposed concept attempts to transform conventional construction sites into on-site assembly environments. Inspired by the self-climbing crane and special crane application in the ship building industry, the on-site construction factory is designed to assemble the building with minimal human intervention. Supported by a GCF on the ground floor, which is mainly responsible for shipping/receiving, restoration, and assembly, there is a perpetual SCF responsible for the erection process on top of each tower. Each one of them can independently function, extend and retract, and they operate under a specific protocol that improves construction efficiency and safety (see Figure 13) [34].

When the section of the wing is completed, the SCF will be retracted, hoisting equipment will be dissembled, and the vacant frame structure will be lowered into position and will function as the roof of the building. Apart from the central SCF, each wing SCF is equipped with two automated gantry cranes. The gantry crane will cover the entire construction shop floor of the building. The central SCF benefits from an automated gantry crane and a jib crane. The jib crane is responsible for vertical material transportation for the central SCF and carrying out the initial construction of the other four SCFs.

The hoist module functions as the end effector of the automated gantry crane, which is equipped with the smart

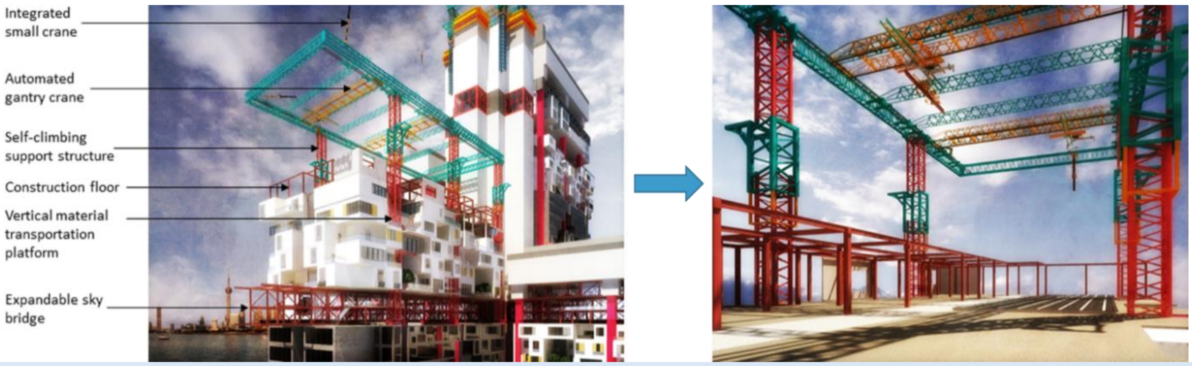

Figure 13. Exterior and interior views of the sky construction factory

crane hoist system to keep delivery balanced as well as to provide vertical and horizontal transportation of the building components. The hoist module is also equipped with a sensor-controlled configuration system to help identify the location of the panel and following pre-programmed assembly sequences. The motion displacement of the robot can be manually operated, and in case of emergency, it will switch to an autopilot control system. The robot control system is connected with the main site control facilities and the project management information system [35]. Once the building components with the auto-alignment feature reach the correct assembly location, the connections will be fastened by means of the dry connection method. Bolting and on-site assembly activities will be implemented by single-task construction robots to increase assembly speed.

The vertical material transportation platform is controlled by a lifting planning system that generates a lifting plan based on data such as floor heights, acceleration distance, reduction time, number of stops, construction material input speed, lifting cycle, material transfer speed and waiting time. The data required can be collected from the RFID and ZigBee sensors which are located on the building structure or embedded in the building materials [36]. The base of each tower will function as a material loading, sorting and pick-up station during the construction, expansion and maintenance process. A programmable logic controller (PLC) is used for controlling the picking system. In the off-site factory, each building component is allocated with a RFID tag. When they arrive on site, the tag will be scanned and the information will show the exact assembly sequence and assembly position of each component. Then the components will be placed onto the picking station in the correct order, ready for lifting and assembly [37].

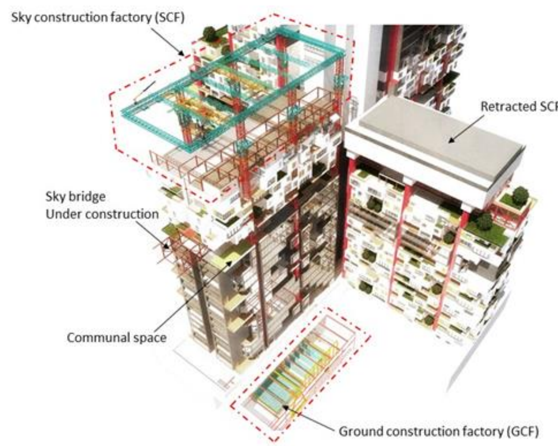

Figure 12. Sky construction factory and ground construction factory

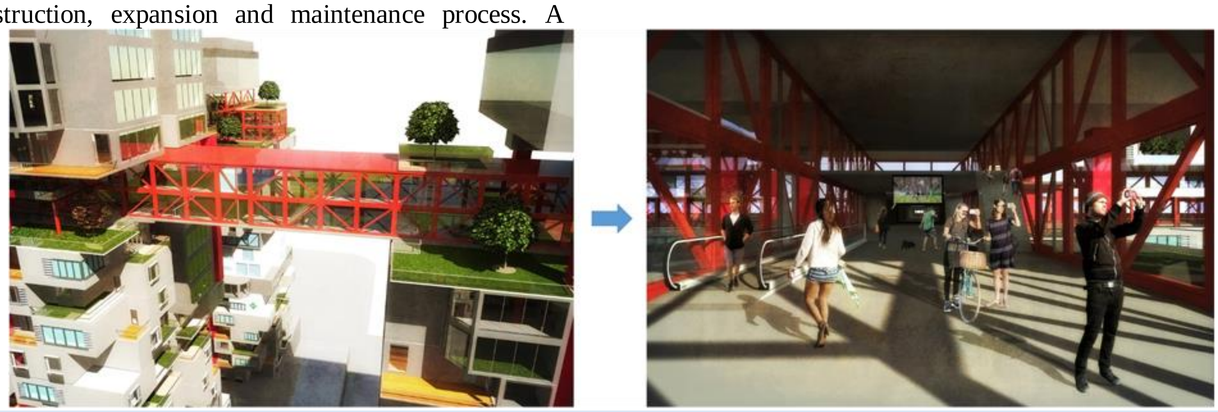

Figure 14. Exterior and interior views of the sky bridge

Sky bridges

The sky bridge, which serves as the main horizontal paths or streets connecting different towers, as well as a community gathering space for multiple activities [38], will be assembled by the correspondence SCF that depends on the direction where the sky bridge will extend. The SCF will be extended by using a smaller integrated crane on the upper deck of the mainframe structure. Then, the automated gantry crane will construct the sky bridge. Eventually, the sky bridge shall be interconnected from either side by using integrated retractable assembly systems (see Figure 14). Various means of mobility technology such as travellators and rope-free elevators [39] can be utilized within the sky bridges and central building cores to catapult the efficiency of internal transportation.

Open building approach

Following the Open Building concepts, the building system of dynamic vertical urbanism can be divided into 4 sub-systems: structures, non-load-bearing components, services and construction. In general, structural systems include a series of steel beams and columns that are interconnected and provide a flexible box-shaped support system. The prefabricated concrete double ribbed floor panel also classifies as part of the structural system. Non-load-bearing component systems include precast concrete floor panels and sandwich wall panels. Services system consists of interior fixtures, electrical, plumbing fixtures, and heating, ventilation and air conditioning (HVAC) of the building. Each part can be easily assembled or disassembles so that the building system is able to be upgraded or modified according to the specific demand of each end-user (see Figure 15).

Process information modeling platform

In order to establish the central "nervous system" of the proposed vertical city concept, the concept of Process Information Modeling (PIM) is introduced based on the accumulated progress in BIM. In general, PIM aims to provide a collaborative way of planning, designing, producing, assembling and managing throughout the entire project life cycle. The main objective of PIM is to adopt the current BIM technology and supplement it with a process-oriented database platform, allowing for smooth data transfer, as well as promoting seamless and constant data sharing among all stakeholders. Digital documentation, simulation and real-time data are progressively produced to support the decision-making process. The PIM platform will collect real-time information from dedicated data clusters, then store, categorize, process, and distribute the most relevant information to the right stakeholder at the right time. In the same manner as the proposed dynamic vertical urbanism concept, at the time of writing this paper, PIM is under conceptual development. Based on the current research progress of the PIM technology, Figure 16 shows the preliminary system architecture of the proposed PIM platform for developing the entire life cycle of the dynamic vertical urbanism complex [40].

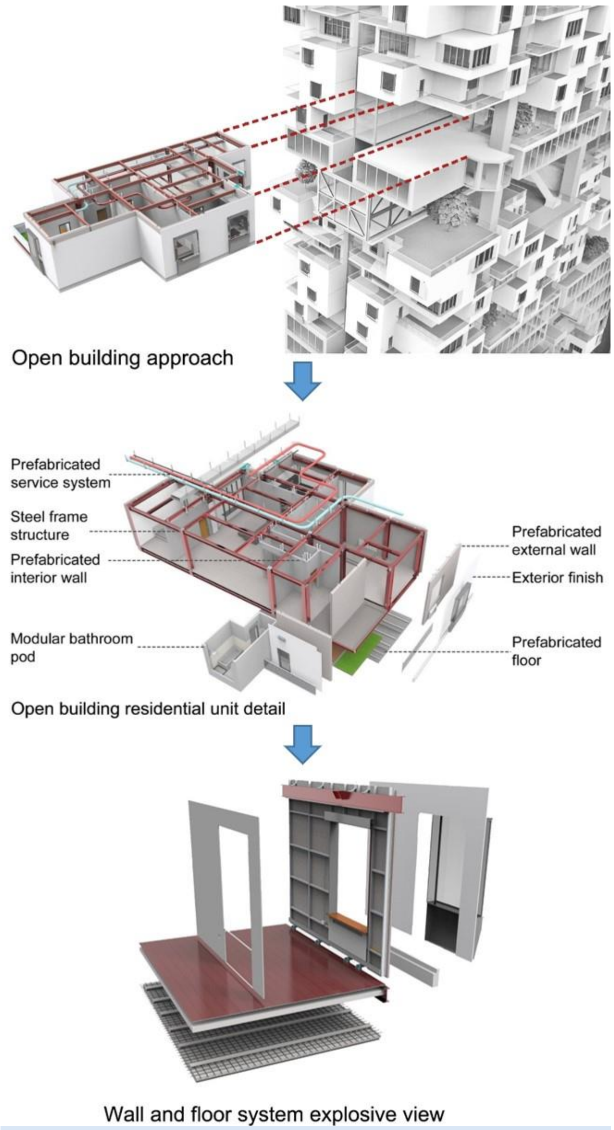

Figure 15. Open Building analysis in dynamic vertical urbanism

Development scenarios

In general, the construction of the building follows a bottom-up approach, working from the ground section up. The construction sequence consists of six main procedures: First, the assembly of the initial on-site construction factories; second, structural assembly, in which the steel beams, columns and the floor components are assembled; third, external façade finishing; fourth, service installation, and interior decoration; fifth, preparation or removal of the temporary installation fixtures, anchor systems; finally, the entire SCF will be jacked up by the self-climbing structure. The building component will be installed following a programed pattern.

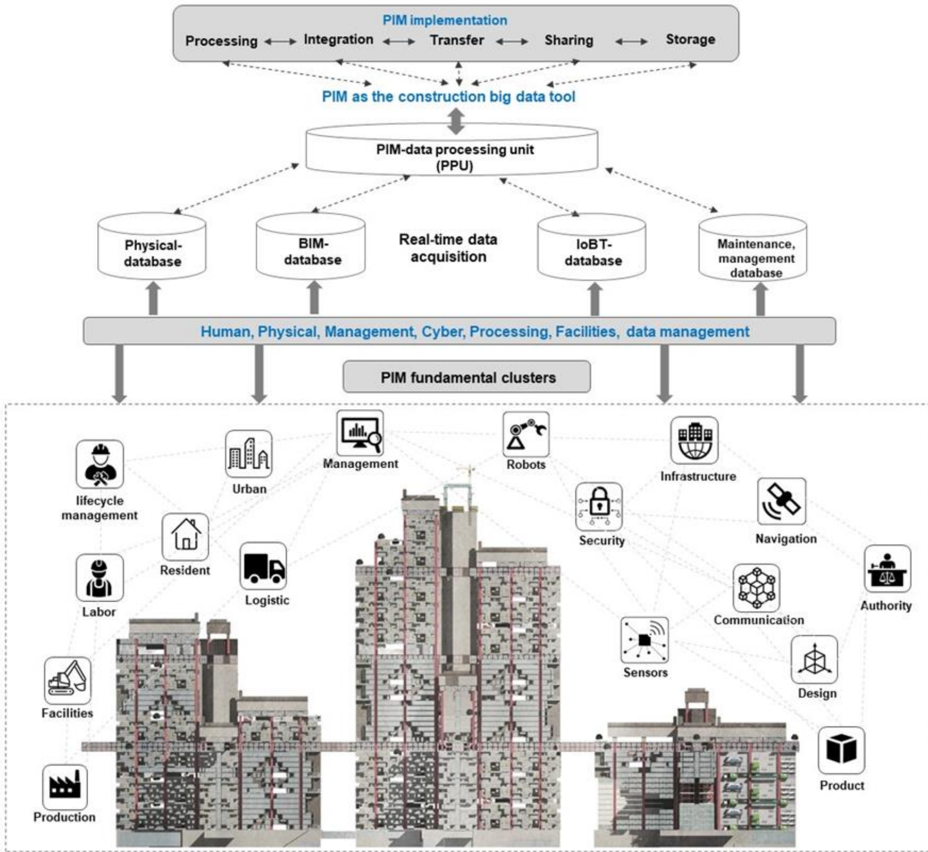

Figure 16. Proposed PIM framework to manage the entire life cycle of the proposed approach

A specific sequence of crane and robot manipulations will occur, which is synchronized by the project control program. When reconfiguration of the building is required, the interior can be easily modified; when relocation and deconstruction are required, deconstruction can be conducted in a reversed order to the construction process. One possible scenario for the future development over the lifecycle of a complex following the principles of dynamic vertical urbanism is envisioned in Figure 17 and the future vision of this complex is visualized in Figure 18 and 19.

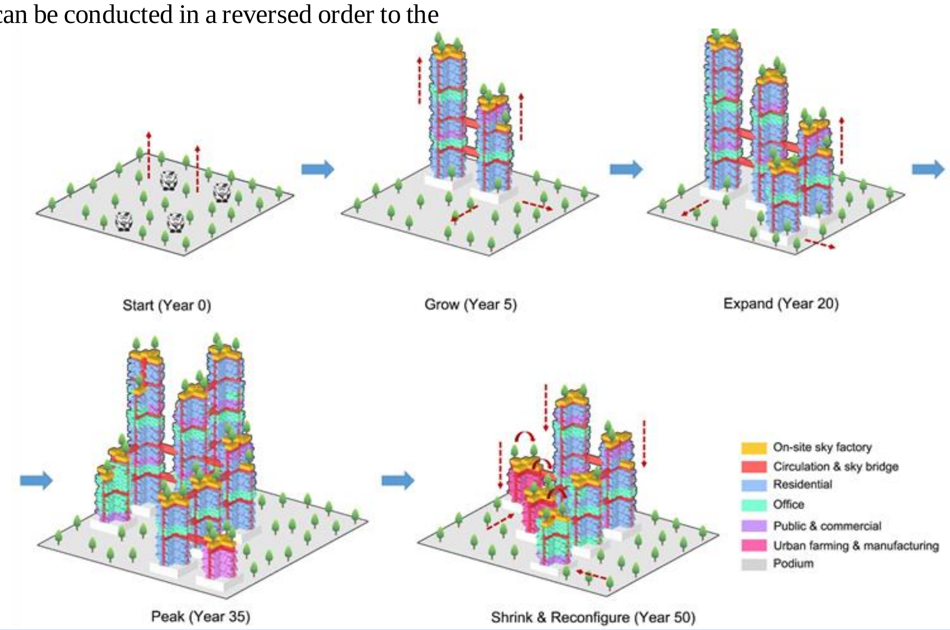

Figure 17. An exemplary scenario of 50-year development of a complex based on dynamic vertical urbanism

Figure 18. Visualization of the roof garden of a dynamic vertical urbanist complex

Figure 19. The future vision of a dynamic vertical urbanism complex in Shanghai's suburban context

Discussion

In this section, the limitations of the proposed framework, the future work to overcome them, and the novelty of this research will be discussed.

Limitations and future work

Like any other conceptual frameworks of building typology, this framework surely has its limitations, including: (1) The conceptual framework is not yet verified; (2) the feasibility of the integration of the sub-systems (i.e., the "six pillars" of dynamic vertical urbanism) into one building system is not validated; (3) the proposed framework might have features that do not comply with current building code and regulations (e.g., early or continuous occupation of the building complex when it is under construction or expansion, novel construction methods which are not widely known or utilized in the current construction practice, etc.); (4) the cultural aspects of this framework in architecture are not yet discussed. Therefore, the next steps of the research should be conducted as follows.

(1) The framework should be further verified and optimized according to the feedback from the academia and industry. This would help to refine the proposed framework and theory based on the knowledge and experience of a broader audience.

(2) Conduct feasibility studies, partly/fully validating and implementing the proposed sub-systems with potential pilot projects. The development of pilot projects will further attract industry deployment, introduce specialized construction equipment and multi-task construction robots, and enhance Human-Machine Interaction within the construction industry to promote new measurement techniques improving work environment safety.

(3) As the validation phase progresses, the details of each sub-system must carefully examined and finetuned in order to comply with the local building code and regulations. Furthermore, researchers, city planners, and policy makers should seek to improve the existing regulations and even establish new standards as a response to the rapid-changing construction technology, urban environment, and societal circumstances.

(4) The architectural design of each building complex must involve an in-depth understanding of the local context, including the natural environment, cultural practice, and aesthetic preference of the particular location. This endeavor can help to improve the acceptance of buildings based on the proposed framework.

Novelty

This paper provides a bold reconsideration of vertical city in the name of dynamic vertical urbanism, enabling constant vertical urban transformation by applying the state-of-the-art building theories and technologies. Six interconnected concepts and technologies constitute dynamic vertical urbanism, including five city elements, Robot-Oriented Design, Open Building concepts, modularization and industrialized prefabrication, on-site automation, and Building Information Modeling. A novel framework of vertical city, or in other words, dynamic vertical urbanism, covering the entire life cycle of a construction project and featuring constant vertical urban transformation by applying the state-of-the-art construction technologies is proposed.

This proposed framework demonstrates a significant first step to fill the research gap between current skyscraper projects broadly entitled "vertical cities" and the missing trait of a city, which is its ability to continuously grow and transform in terms of forms and functions. Furthermore, the framework is highly flexible and replicable so that architects and civil engineers around the globe are able to propose their own customized and localized interpretations of dynamic vertical urbanism based on the six-pillar principles. In addition, this research raises public awareness and promotes involvement for the research and development of construction automation and robotics. In the meantime, it can assist architects and urban planners to formulate a future framework for building design, urban planning, and policy-making process to benefit all potential stakeholders, and provide an inspiring way of thinking to tackle the aforementioned serious issues, such as overpopulation, population aging, land shortage, lack of infrastructure, and environmental pressures. More importantly, it is possible that the results of this research will potentially establish topic-specific or spin-off research areas in various disciplines.

Nowadays, due to the improvement of medical care standards, the enhanced social security level, and the implementation of the three decade-long one-child policy which was recently replaced by the two-child policy since 2015, China is about to accelerate into an aging society [41]. Meanwhile, issues such as rapid urbanization, severe environment pressure, and increasing labor costs will further challenge the stability and sustainability of China's development. Given that the technical barriers for the popularization of construction automation technology have substantially diminished due to the rapid development of information technology and robotics, the construction automation technology will soon provide a great opportunity to tackle those critical issues. The proposed framework is meant to be tailor-made for the Chinese construction industry, but it will have wider audiences once the industry sector is ready to be reformed. For example, the future construction sector will expose a cross-disciplinary characteristic that will allow many industries and disciplines to coexist and collaborate. In this sense, upgrading the performance of the construction industry will not only have a positive impact on one industry, but also grant much larger contribution to the prosperity of many in the future [42].

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