Council on Tall Buildings and Urban Habitat Korea

International Journal of
High-Rise Buildings
www.ctbuh-korea.org/ijhrb/index.php

International Journal of High-Rise Buildings
June 2022, Vol 11, No 2, 75-86
https://doi.org/10.21022/IJHRB.2022.11.2.75

Towards Instant Availability and Full Life Cycle Resilience in Vertical Cities: Automated Deployment and Transformation of High-Rise Buildings to Mitigate Social Challenges

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Abstract High-rise buildings often can accommodate the population of small horizontal cities. The investment in high-rise buildings is considerable and therefore a rapid return on investment is necessary. The immediate availability of high-rise buildings can be achieved by automated prefabrication of highly finished modules and their instant on-site assembly by robotic and automated construction sites. A high-rise building as a vertical city can be considered as a sophisticated organism that can constantly change throughout its lifecycle in response to economic growth, demographic change, and environmental pressures. To date, many new urban high-rise developments claim to be "vertical cities", yet few represent this important characteristic. This article analyzed the technological readiness and innovations in the field of construction automation and robotics including single-task construction robots, automated on-site construction factories, and ambient assisted living. These technological advances enable the realization of future vertical cities that are able to continuously grow and transform in terms of form and function. Finally, the article proposes a visionary archetype of vertical city in the name of "dynamic vertical urbanism" that is easy to expand vertically and horizontally in order to achieve instant availability and full life cycle resilience thanks to advanced building technologies.

Keywords Automation, Construction Robots, High-rise, On-site Construction Factory, Vertical City, Building Automation

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1. Introduction

A high-rise building as a vertical city is a metabolism that is constantly changing throughout its lifecycle as a result of economic shifts, demographic change, and environmental pressures. Nowadays, global megacities are facing unprecedented issues such as overpopulation, population aging, land shortage, ghost cities, and environmental pressures during the process of uncontrollable urban sprawl (Li et al., 2019). 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. If the form and function of a high-rise building cannot be changed, when the surrounding environment and social factors change, the building will not be able to change the fate of being demolished, which leads to a huge waste of resources. A well-known example was the demolition of Pruitt-Igoe in St. Louis, Missouri, USA (Samaratunga and O'Hare, 2013). This article aims to explore a novel framework of high-rise building clusters as vertical cities, 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

2. Literature review: technological readiness and innovations

After the first experiments of large-scale industrialized, automated and robotized pre-fabrication of system houses were conducted successfully in Japan, and the first products

of modular houses (e.g. Sekisui Heim M1, 1968 by K. Ohno) also proved successful in the market, companies such as Toyota Homes, Sekisui House, Misawa Homes, Sekisui Heim, and Daiwa House started to manufacture approximately a quarter million modular houses per year (Linner and Bock, 2012). The main Japanese contractor Shimizu, 1975 in Tokyo, set up a research group for construction robots. The goal was now no longer the mere shifting of complexity into a structured environment as in prefabrication, but the development and deployment of systems which were able to be used locally on the construction site to create structures and buildings. The focus initially was set on simple systems in the form of so-called single-task robotic systems that can execute a single, specific construction task in repetitive manner.

At the end of the 1970, Shimizu and other Japanese general contractors conducting large building and infrastructure construction projects saw a huge potential in such construction robots. Finally, with the beginning of the robot boom in the early 1980s in which automation and robot technology in all industries in Japan suddenly spread substantially, for the Japanese construction industry the theme became so up to date that eventually even the Japanese government started to promote and bring forward the subject - also partly due to the chronic shortage of skilled workers in Japan. Finally, in 1978, the Japan Industrial Robot Association (JARA) under guidance of the Ministry of International Trade and Industry (MITI) established a commission headed by Professor Yukio Hasegawa for the analysis of applications and development of automated systems and robotic technology in construction. Participants of this commission were mostly young and motivated engineers of major Japanese construction companies and general contractors. Quickly the commission became a “stem cell” for new concepts and step by step specific research projects and robot systems were set up and implemented by the companies.

Numerous universities followed this trend. Thus, the Waseda University for example founded the legendary WASCOR group (Waseda Construction Robot) which now started to develop automated and robotic construction technology from an interdisciplinary, cross-sectoral approach. In the early 1980's there followed then also coordinated activities of the large, national research institutes. In 1983 the Architectural Institute of Japan (AIJ) and its commission, responsible for building materials and construction methods, implemented a 15-headed group for automation and robotics in construction. Shortly afterwards, the Japan Society of Civil Engineers (JSCE) followed, and from 1985 the renowned Building Research Institute of the Japanese Ministry of Construction (BRI) started to work with the Centre for Development on systems for robotic assembly (i.e., Solid Material Assembly System, SMAS). In 1987, the Building Contractors Society (BCS) whose members were from the major construction companies, started to conceive a systemic assessment of the need and potential of automated and robotic technology in particular for sub-contractors, equipment manufacturers, and construction equipment rental companies.

The reasons for the synergistic activities of the government, national research institutes, general contractors, and academic institutions had both political and socioeconomic back-grounds. For example, the low productivity in the construction industry compared to the manufacturing industry, the skilled labor shortage, the aging of construction workers, the increasing poor workmanship and occupational diseases, and poor working conditions, were controversial discussion topics in the public. The building industry that traditionally had high reputation in society in Japan thus faced strong pressure to improve its working environment and public image.

All in all, following institutions were involved in the development and deployment of automated and robotic technology during the 1980s and 1990s (first in the form of single task systems and later on in the form of integrated automated sites) for on-site building construction:

- Japan Robot Association (JARA)
- Ministry of Industry and Trade (MITI)
- Waseda Construction Robot Group (WASCOR)
- Ministry of Construction
- Architectural Institute of Japan (AIJ)
- Building Contractos Society (BCS)
- Advanced Construction Technology Center (ACTEC)
- Japan Society of Civil Engineers (JSCE)
- Building Research Institute of the Japanese Construction Ministry (BRI)
- Research Institutes of big construction companies (Shimizu, Obayashi, Kajima, Maeda, Goyo, Toda, Taisei, Fujita)
- Manufacturers of Automation and Robot Technology
- Construction/manufacturing equipment suppliers (e.g. Komatsu, Hitachi, Mitsubishi, etc.)
- Universities: Wasedsa University, University of Tokyo

Accordingly, R&D investment for automated and robotic technology (first in the form of single task systems and later on in the form of integrated automated sites) for on-site building construction during the 1980s came from sources such as the budget of construction companies, equipment suppliers, Japan Ministry of Construction, and manufacturers of automation and robot technology (see Figure 1).

2.1. Single-task construction robots (STCRs)

STCRs are systems that support workers in executing one specific construction process or task (e.g. digging, concrete leveling, concrete smoothening, painting) or completely substitute the physical activity of human worker that is necessary to perform this one process or task. To date, the application of STCRs has expanded to almost all areas in construction. For instance, researchers summarized 200 existing STCR systems into 24 categories

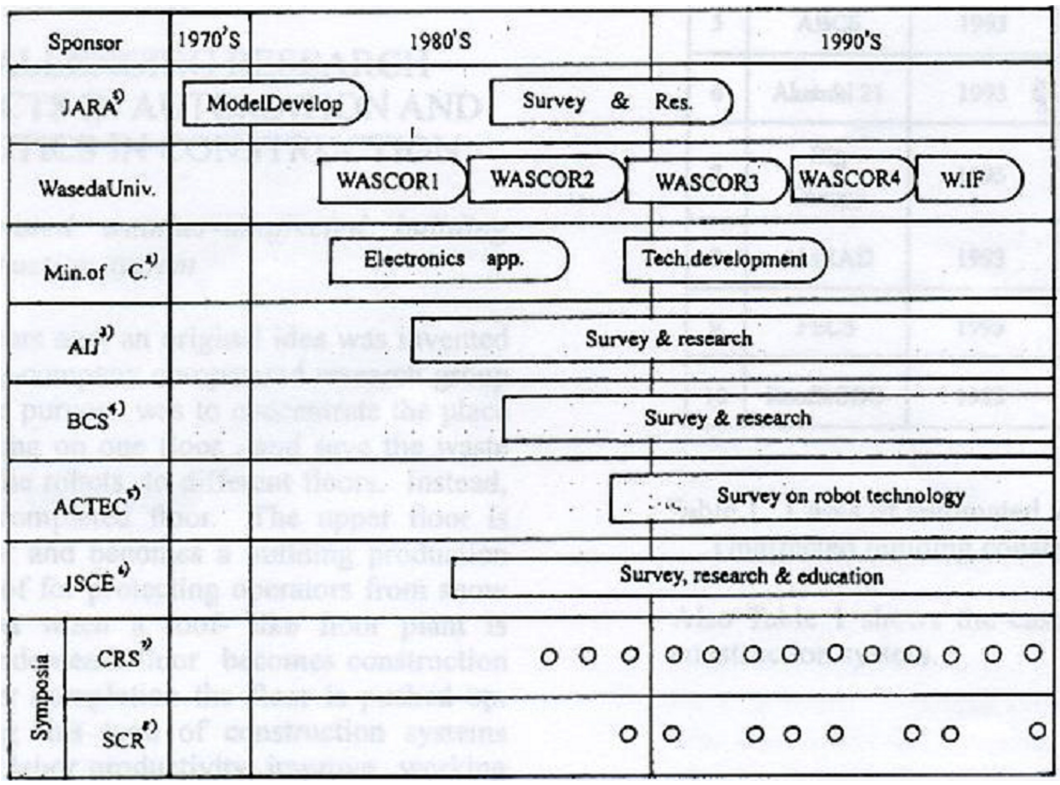


Figure 1. Timeline of the early R&D activities on construction automation and robotic technologies.

based on their functions including but not limited to rebar handling, concrete distribution and leveling, site logistics, component positioning, steel welding, façade processing, tiling, interior finishing, recycling, maintenance and inspection (Bock and Linner, 2016a). The processes and tasks that they support or substitute can be allocated to a specific profession or craft. Furthermore, the processes and tasks for which STCRs were developed have in common that they necessitate a high rate of repetitive sub-activities. Further common characteristics of STCRs are:

- They are highly specific not only for a profession but even for a task within a profession (e.g. different systems for concrete poring, leveling and smoothening which all fall under the realm of the profession "floor layer")
- They have enhanced productivity compared to conventional labor-machine based execution of work tasks
- Positive impact on the quality through precise control of functions and operations (e.g. uniform distribution of paint) and by allowing that execution recorded or monitored in real time
- Improvement of working conditions: dangerous and heavy physical work is reduced
- Most robot allowed various operation modes: automatic-sensor guided, automatic pre-programmed, remote controlled
- Positive impact on resource consumption through precise automatic control (e.g. painting robots allowed that the amount of paint was precisely controlled and that spare or spread paint was collected and reused.
- In most cases simple but robust sensor technology: gyroscope, simple laser systems, touch/pressure sensors
- Usually no more than one or two persons are necessary to operate the systems.

As in any other industry, concepts of modularity developed slowly and gradually over time. Modularity and thus adaptability to multiple work processes or tasks was not a feature of the STCRs from the beginning. This reduced the operational scope of the systems and enhanced, despite the above-mentioned beneficial characteristics, the cost of the robot systems, as thus one was not able to distribute those cost over various work activities (as e.g. in the case of conventional multipurpose construction equipment). Some companies introduced modular approaches only in later robot generations (e.g. Komatsu/Kajima) and in integrated automated construction sites (e.g. in the form of allowing for end-effector change).

The fact that STCRs operated task specific made them on the one hand highly flexible (they could be used along with conventional work processes and did not necessitate that the whole site is structured and automated), but also stated a major weakness. As they were in most cases not integrated with upstream and downstream processes, demanded safety measurements, and hindered parallel execution of work tasks by human workers in the area where they were operated, productivity gains were often

equalized. In addition, all the setup of the robots on the site (equipment, programming) was time consuming and demanded new skills. Further, the relocation of the systems on the site was in many cases complex and time consuming. It is outlined as follows how the evaluation of the first generations of developed and deployed STCRs and the identification of the above-mentioned problems led from 1985 on stepwise to the concept of integrated automated construction sites.

2.2. Automated on-site construction factories

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 (Maeda, 1994). There are four basic 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, Japanese construction company Shimizu developed the first automated high-rise construction system called SMART. It was a sky factory moving upwards supported by building. The SMART sky factory roof structure (and the subsystems attached to it) is assembled on ground floor and then lifted along the supporting steels into a height in which the operation can start. In the beginning the supporting steels rest already on the finished basement levels. After the construction of the first floors by the system the steels/climbing mechanism can use these newly constructed floors to lift the sky factory. Full utilization of the sky factory (including its capability to provide structured work environment also from outside façade work on N-3 level) can start from the 3rd floor on. Further after the construction of the 4th floor a material handling system can be deployed on ground level. After dismantling of factory covers and manipulators the roof structure of the sky factory can be integrated into the building as uppermost floor (e.g. as service floor containing aeration system etc.).

The SMART system concentrates work activities in a sky factory. In contrast to other systems the overhead manipulators do not have a fixed main trajectory but can travel freely in the whole system. Up to 25 manipulators (trolley hoists) can operate in parallel and travel from the material handling space on the ground floor, over an automatic lift into the sky factory where they can move to any com-ponent installation location via a (also movable) gantry rail system. Further in contrast to other systems the steels which support the sky factory and are part of the climbing mechanism do not rest on top of columns but between the columns - thus the climbing process has less interference with the component assembly process. Within the sky factory, work is done on three four levels in parallel. In the uppermost floor (N) components are positioned and aligned. In the lower floors, activities such as fixation, interior finishing and façade work (over platforms provided by the sky factory) are done. Once the sky factory moves a floor higher, at its mower end a completely finished floor leaves the factory.

A system of mobile overhead cranes is synchronized with the building shape and the column grid system of the building. Multiple mobile overhead cranes travel in fixed direction lengthwise the building. However, the trolley hoist manipulators can travel between the cranes broadside. Thus the trolley hoist manipulators can travel to any point in x/y (lengthwise/broadside) direction. As the steels supporting the sky factory structure do not rest on the columns but between the columns, they do not permit the trolley hoists to position components directly over a column. The trolley hoists pick up components on the ground floor, travel with the component over the vertical automatic lift into the factory and then travel over a transport channel (multiple mobile overhead cranes build a line) allowing the trolley manipulators to move along it.

The SMART system manufacturing the building on the site (system) by a sky factory consists of a multitude of integrated sub-systems. The trolley hoist manipulators travel by automatic vertical lifts and automatic overhead cranes freely in the systems. They thus integrate vertical and horizontal delivery system and erase the necessity of handing over components between those and thus eliminate waste processes (as waste in other systems occurring through the handover between vertical and horizontal delivery system can be considered e.g., rest of component, time necessary to accomplish handover, damage to component during handover). The sub-systems include the material handling system on the ground, the sky factory structure and enclosure, the climbing system, the trolley hoist manipulator system, the robotic welding system, and the sub-system for management and real-time control (see Figure 2).

Ever since the success of SMART, construction companies and research institutes around the world developed a variety of automated construction systems. Researchers analyzed and summarized various types of on-site construction factories based on the techniques developed by different construction companies around the world (Bock and Linner, 2016b), see Table 1.

However, new developments show that major Japanese construction companies today return to single-task-like approaches. Today Obayashi for example uses its integrated, automated construction site (Automated Building Con-

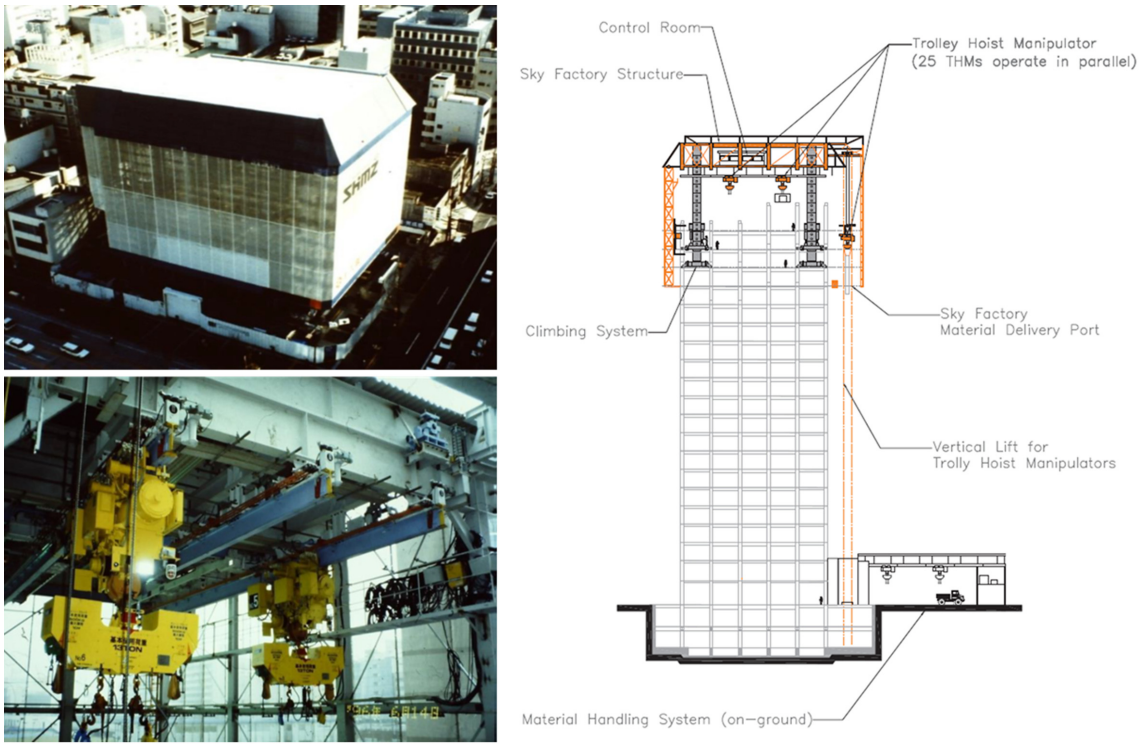


Figure 2. Early stage construction site (top left), trolley hoist manipulators (bottom left), and section (right) of the SMART system.

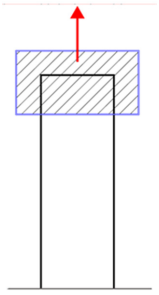
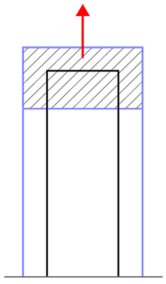
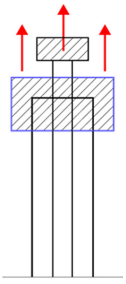
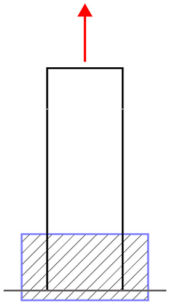
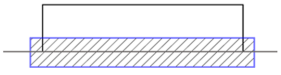
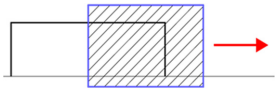
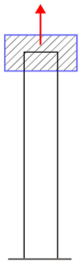
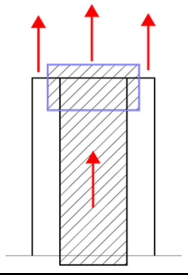
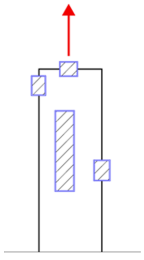
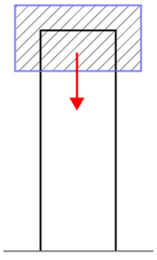
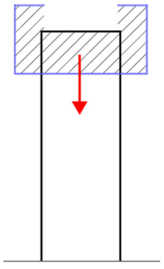
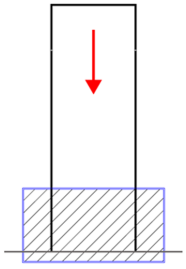
struction System, ABCS) not as a total system anymore, but applies some of its subsystems as single task systems (e.g. automated logistics system, welding system). By not directly and rigidly connecting those systems Obayashi gains workshop like flexibility (in contrast to chain-like organization to which integrated sites were oriented), is necessary when constructing buildings such as the Tokyo Sky Tree which is not only an individual building but also changes its shape several times from bottom to top. New management approaches, grown knowledge about the deployment, work process integration of single robotic or automated applications, and digital work process management and control software influence the integration of such systems positively and enhances their efficiency compared to the first-generation systems deployed during the 1980s. The development and deployment of STCRs are thus today, in times where more and more individuality of any product is demanded, more relevant than ever (Bock and Linner, 2016a).

2.3. High-rise buildings (vertical cities) transformation by modular ambient assisted living (AAL) technology

Due to the high investment cost in high-rise buildings (vertical cities) and their ecological impact and considerable footprint, modern cities cannot afford to "scrap and build". In order to adjust to demographic changes, the Chair of Building Realization and Robotics at Technical University of Munich developed a novel interior building module called Personalized Intelligent Interior Unit (PI^2U) since more than two decades ago. It can be considered as a gerontechnological solution for aging society that focuses on providing people with technological assistance mainly in their natural living environment. The original ideas can be traced back to the 1980s. Sponsored by Japan Science Society anticipating future challenges of ageing society, one of the first concept was the life support system (LSS) for aging society developed by Thomas Bock in 1988, depicting visionary functions such as assisted dressing, smart home control, automated body turn-over, telemedicine, and emergency evacuation (see Figure 3). The concept was inspired by Bock's experience with the LSS for astronauts in space during his studies with space architecture professor Larry Bell from University of Houston, Texas, where he researched on the NASA Tech House built in Langley, Virgina, USA in 1979.

After the first concepts, many AAL systems and projects have been developed over the years. As the population aging crisis deepens, there will soon come a time when the current way of taking care of older adults is both socially and economically unsustainable due to the continuously increasing older population and severe labor shortages. For example, the Chair of Building Realization and Robotics at Technical University of Munich carried out a series of research projects addressing different aspects of activities of daily living (ADLs) such as exercising (GEWOS), mobility (PASSAge), working (USA^2), independence (LISA Habitec), fall detection

Table 1. Various type of on-site construction factories

Sky factory (moving upwards) supported by building	Sky factory (moving upwards) on steels	Sky factory pulled up by core (main factory and core factory moving upwards)	Ground factory (stay in fixed place, vertically oriented building) and building push-up
			
Ground factory (stay in fixed place, horizontally oriented building) and building push-up	Self-supported ground factory (horizontally moving)	Sky factory (moving upwards) for simple tower manufacturing	Centralized sky factory (moving upwards) combined with conventional construction
			
Decentralized sky factory (moving upwards) combined with conventional construction	Closed sky factory supported by building (moving downwards)	Open sky factory supported by building (moving downwards)	Ground factory (fixed place) and building lift-down
			

(BaltSe@nior), and physical/cognitive rehabilitation (REACH) (Bock et al., 2019), which can be easily and rapidly deployed in older adults' living environment (see Figure 6).

3. Future vision

First ideas of vertical city emerged back in early 1980s where Thomas Bock proposed one of the first mixed-use skyscrapers in the Loop area of Chicago in order to avert "ghost downtown" effect after 5 pm in his master thesis at Illinois Institute of Technology which was advised by Prof. Myron Goldsmith and Prof. Fazlur Kahn. The proposed building employed a bundled tube structure that had a height to diameter (H/D) ratio of 9.0, which was slenderer than most other skyscrapers in the US during that time. In addition, the structure was carefully calculated particularly to withstand Chicago's strong wind loads. The proposal won Best American Thesis Award from Harvard University in 1982 (see Figure 4).

To date, more and more new urban high-rise complexes claim to be "vertical cities", yet very few represent the essence of a city, which is the ability to continuously grow and transform in terms of forms and functions (Hu et al., 2020).

Based on the analyses in the previous sections, a comprehensive and dynamic approach can be proposed to develop the vertical city in the name of dynamic vertical urbanism (DVU). First of all, the novel vertical city complex follows five key city elements (Lynch, 1960), namely 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. Furthermore, each tower is overstructured and

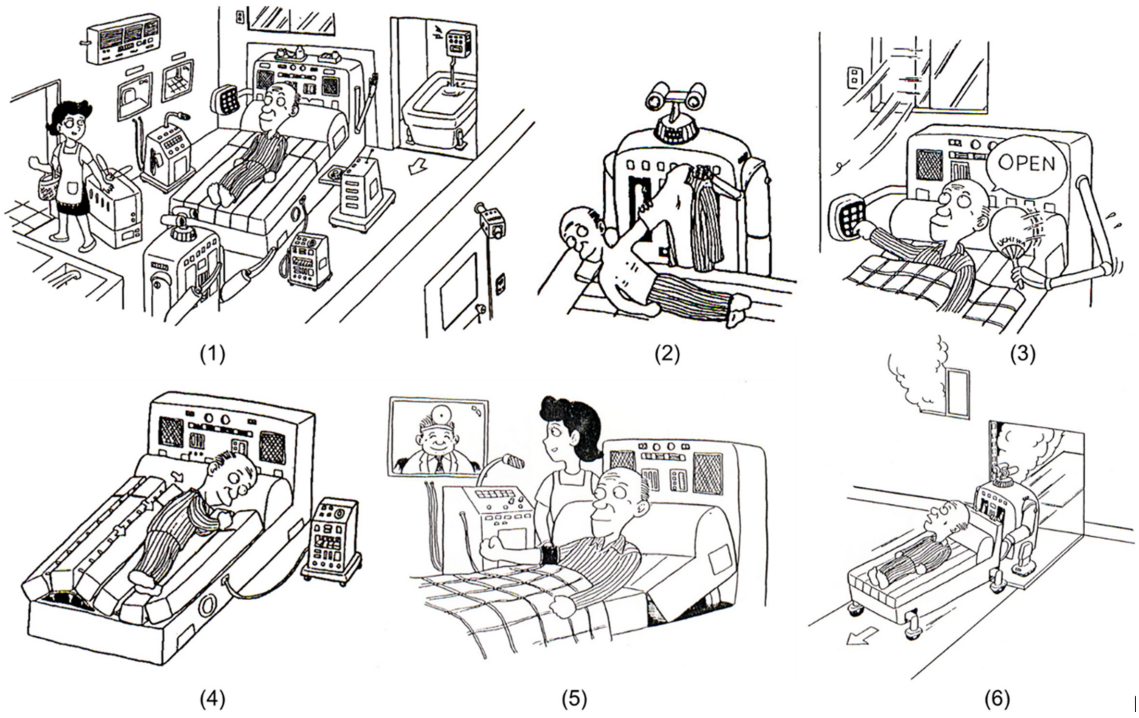


Figure 3. First concept of life support systems for aging society in Japan envisioned by Bock.

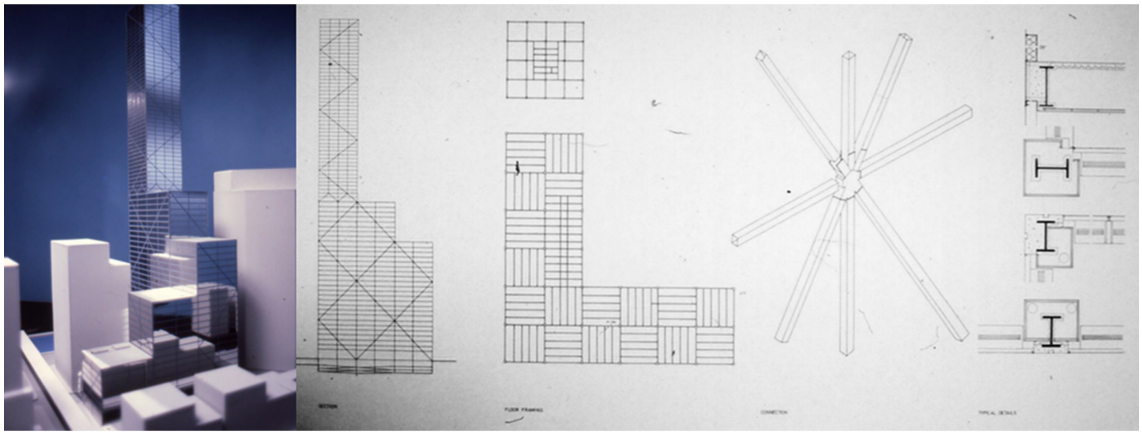


Figure 4. The model and structural design of the initial "vertical city" proposal.

equipped with an on-site construction factory to enable future expansion to a certain extend. In addition, the proposed design complies with the design principles of sustainable skyscrapers concluded by Wood (2015), including variation with height, new programs, communal spaces, envelope opacity, sky bridges and integrated vegetation.

The proposed archetype demonstrates a type of cross-shape floor plan that can be easily expanded vertically and horizontally. 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. 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 construction factories are located.

It is vital to adopt automated construction factories in order to limit the effects of hostile environments on robot performance as well as to offer a clean, quiet, and unobtrusive worksite environment to permit early and continuous occupation of the residents. The sky construction factory (SCF) and the ground construction factory (GCF), which make up the on-site construction factories (OCF), are critical to the development of DVU. The suggested approach aims to transform traditional construction sites

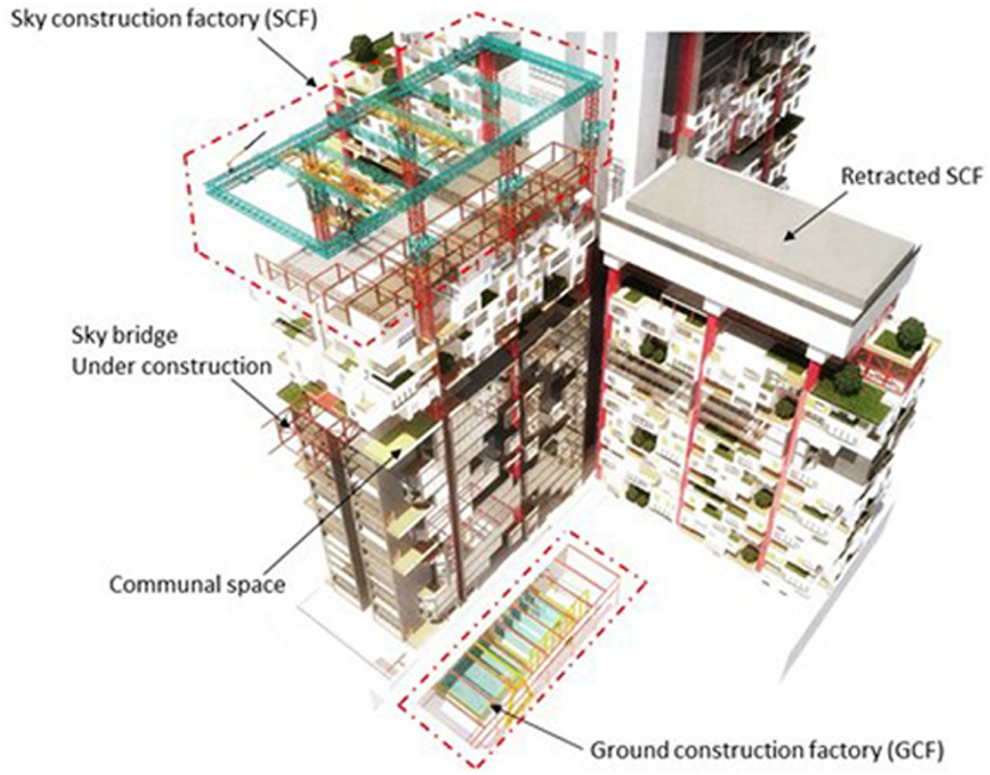


Figure 5. Sky construction factory and ground construction factory in the DVU archetype.

into on-site assembly environments through the use of industrialized building design and automation technology. The on-site construction factory was inspired by the self-climbing crane and specific crane application in the shipbuilding sector. It is designed to assemble the building with minimal human interaction. Supported by a GCF on the ground floor, which is primarily responsible for shipping/receiving, restoration, and assembly, there is a perpetual SCF responsible for the erection process on top of each tower. Each one may function independently, extend and retract, and operate according to a set of rules that enhances construction efficiency and safety (see Figure 5).

When the wing portion is finished, the SCF will be retracted, the hoisting machinery will be dismantled, and the unoccupied frame structure will be dropped into place and serve as the building's roof. Each wing of the SCF has two automated gantry cranes apart from the central SCF. The gantry crane will span the whole building's construction shop floor. An automated gantry crane and a jib crane are located in the central SCF. The central SCF's jib crane is in charge of vertical material delivery and the beginning construction of the other four SCFs.

The hoist module is the end effector of the automated gantry crane, which is fitted with a smart crane hoist system to balance deliveries and enable vertical and horizontal transportation of building components. A sensor-controlled configuration system is also included in the hoist module to assist in locating the panel and following preprogrammed assembly procedures. The robot's motion displacement can be controlled manually, and in the event of an emergency, it will switch to an autopilot control system. The robot control system is linked to the project management information system and the major site control facilities. The connections will be attached using the dry connection method once the building components with the auto-alignment feature have arrived at the precise assembly site. To boost assembly speed, STCRs will perform bolting and on-site assembly tasks.

A lifting planning system controls the vertical material transportation platform, which develops 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. RFID and ZigBee sensors installed on the building structure or incorporated in the building components can provide the necessary data (Murray et al., 2003). During the building, enlargement, and maintenance of each tower, the base will serve as a material loading, sorting, and pick-up station. The picking system is controlled by a programmable logic controller (PLC). Each building component is assigned an RFID tag in the off-site production. The tag will be read when they arrive on site, and the information will reveal the exact assembly order and assembly position of each component. The components will then be positioned in the correct order on the picking station, ready for lifting and assembly (Neelamkavil, 2009).

The sky bridge, which will serve as the major horizontal



Figure 6. Exterior and interior views of the sky bridge in the proposed archetype.

roads or roadways connecting several towers as well as a community meeting area for multiple activities (Wood, 2003), will be built by the correspondence SCF, which will be determined by the direction in which the sky bridge will expand. On the upper deck of the mainframe structure, a smaller integrated crane will be used to extend the SCF. The sky bridge will thereafter be built using an automated gantry crane. The sky bridge will eventually be joined from both sides by integrated retractable assembly mechanisms (see Figure 6). Within the sky bridges and central building cores, various modes of mobility technology, such as travellators and rope-free elevators, can be used to boost the efficiency of internal transit (Morris, 2017). The overall visualization of the VDU archetype is depicted in Figure 7.

The DVU building system can be divided into four subsystems based on the Open Building concepts: structures, non-load-bearing components, services, and construction. In general, structural systems consist of a set of interconnected steel beams and columns that offer a flexible box-shaped support structure. The structural structure also includes the precast concrete double ribbed floor panel. Precast concrete floor panels and sandwich wall panels are examples of non-load-bearing component systems. Interior fixtures, electrical, plumbing fixtures, and the building's heating, ventilation, and air conditioning (HVAC)



Figure 7. A visualization of the proposed complex following DVU principles.

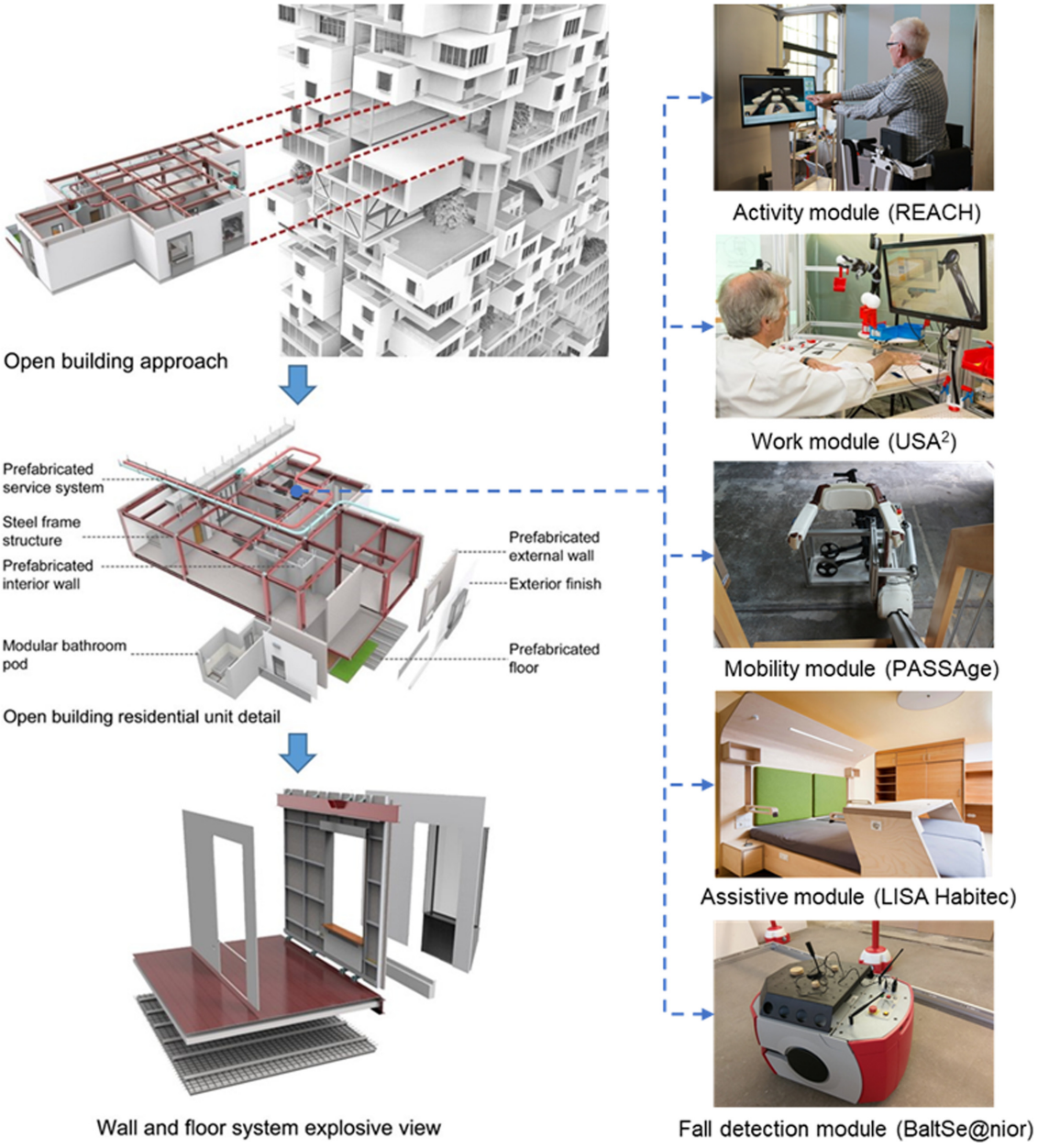


Figure 8. Open Building system in DVU integrating various PI²U systems (external photo source: USA2- Schlegelmilch; LISA Habitec - MM Design).

make up the services system. Any component is readily assembled or disassembled, allowing the building system to be improved or customized to meet the needs of each end-user. Additionally, abovementioned AAL modules can be easily integrated in the modular living units according to each end-user's needs (see Figure 8).

In general, the building is constructed from the ground up, with the ground part being the most important. The construction sequence consists of six main procedures: first, the assembly of the initial on-site construction factories; second, structural assembly, which includes the assembly of steel beams, columns, and floor components; third, external façade finishing; fourth, service installation, and interior decoration; fifth, preparation or removal of temporary installation fixtures, anchor systems; and finally, the entire SCF will be jacked up by the self-climbing structure. The building component will be installed in a pattern that has been pre-programmed.

A predetermined series of crane and robot manipulations will take place, all of which will be synchronized by the project control program. When a building's interior has to be reconfigured, the inside can be easily adjusted; when relocation and deconstruction are required, deconstruction can be done in the opposite order of construction. Figure 9 depicts a probable scenario for a complex's future evolution over its lifecycle, based on the DVU principles.

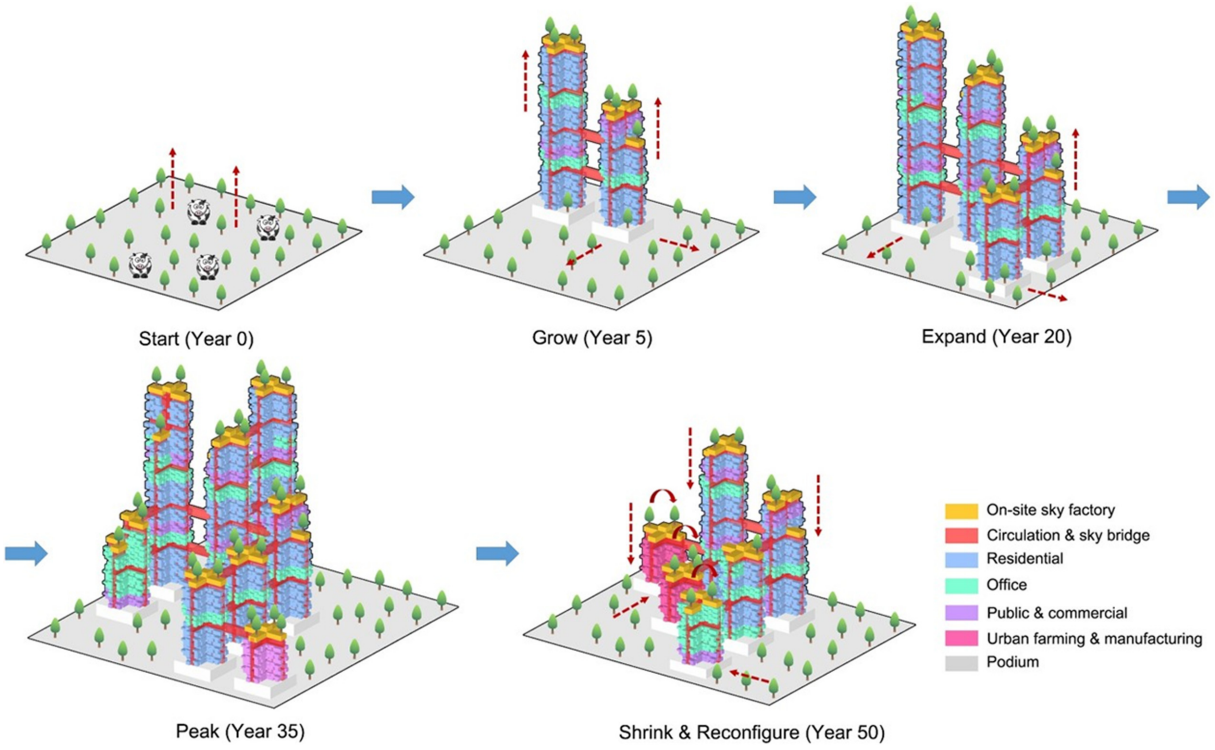


Figure 9. A possible scenario of 50-year development of a VDU complex.

4. Conclusions

In conclusion, the investment in high-rise buildings is substantial and therefore a rapid return on investment is needed. The immediate availability of high-rise buildings can be achieved by automated prefabrication of modular living units and their instant on-site assembly by robotic and automated construction technology. This article summarized the technological readiness and innovations in the field of construction automation and robotics including single-task construction robots, automated on-site construction factories, and ambient assisted living, which enable the realization of future vertical cities that are able to continuously grow and transform in terms of form and function. Finally, a visionary archetype of future vertical city (i.e., VDU) was proposed which is easy to expand and transform vertically and horizontally in order to achieve instant availability and full life cycle resilience thanks to advanced building technologies analyzed in this article.

REFERENCES

Bock, T., Linner, T., 2016a. Construction Robots: Elementary Technologies and Single-Task Construction Robots. https://doi.org/10.1017/CBO9781139872041

Bock, T., Linner, T., 2016b. Site automation: Automated/ Robotic On-Site Factories. Cambridge University Press. https://doi.org/10.1017/CBO9781139872027

Bock, T., Linner, T., Güttler, J., Iturralde, K., 2019. Ambient Integrated Robotics: Automation and Robotic Technologies for Maintenance, Assistance, and Service. Cambridge University Press.

Hu, R., Pan, W., Bock, T., 2020. Towards dynamic vertical urbanism: A novel conceptual framework to develop vertical city based on construction automation, open building principles, and industrialized prefabrication. International Journal of Industrialized Construction 1, 34-47. https://doi.org/10.29173/ijic208

Li, D., Ma, J., Cheng, T., van Genderen, J.L., Shao, Z., 2019. Challenges and opportunities for the development of MEGACITIES. International Journal of Digital Earth 12, 1382-1395. https://doi.org/10.1080/17538947.2018.1512662

Linner, T., Bock, T., 2012. Evolution of large-scale industrialisation and service innovation in Japanese prefabrication industry. Construction Innovation 12, 156-178. https://doi.org/10.1108/14714171211215921

Lynch, K., 1960. Image of the City, The Technology Press & Harvard University Press. MIT Press, Cambridge, MA.

Maeda, J., 1994. Development and Application of the SMART System, in: Automation and Robotics in Construction. pp. 457-464. https://doi.org/10.1016/B978-0-444-82044-0.50064-3

Murray, N., Fernando, T., Aouad, G., 2003. A Virtual Environment for the Design and Simulated Construction of Prefabricated Buildings. Virtual Reality 6, 244-256. https://doi.org/10.1007/s10055-003-0107-8

Neelamkavil, J., 2009. Automation in the prefab and modular construction industry, in: International Symposium on Automation and Robotics in Construction ISARC.

Samaratunga, T., O'Hare, D., 2013. High Density High Rise Vertical Living for Low Income People in Colombo, Sri

Lanka: Learning from Pruitt-Igoe. Architecture Research 2, 128–133. https://doi.org/10.5923/j.arch.20120206.03

Wood, A., 2015. Rethinking the skyscraper in the ecological age: Design principles for a new high-rise vernacular. International Journal of High-Rise Buildings 4, 91-101.

Wood, A., 2003. "Pavements in the Sky": Use of the Skybridge in Tall Buildings, in: CTBUH / CIB 2003 Kuala Lumpur Conference. pp. 325-332. https://doi.org/https://doi.org/10.1017/S1359135503002264