Vertical Gardens in High-Rise Buildings – Modern Form of Green Building Technology

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Abstract. This paper presents the analysis of vertical gardens in selected high-rise buildings located on different continents as an example of the most popular greenery system in contemporary architecture. High-rise buildings designed in the form of vertical garden, use the urban space more effectively and at the same time create a friendlier environment for their residents. In developing large metropolises, these buildings constitute a very important element in design which compensates for the lack of green areas. The first vertical gardens in the form of a system of green walls in buildings were created in the late 30s of the twentieth century. Their inventor was Stanley Hart White. However, a professor of Landscape Architecture at the University of Illinois. However, in tall buildings, these gardens were begun by Patric Blanc in 1994, and then continued by Stefan Boeri. With the development of green wall technology, two general systems have appeared: green walls and living walls. Many of the studies conducted in the world have shown significant environmental and social benefits from the use of vertical gardens in high-rise buildings, despite their significant economic costs. In the presented paper, the green wall system has been characterized on the example of some high-rise buildings, pointing at the determination of benefits from their occurrence in the urban scale as well in the scale of the building.

1. Introduction
The space of modern cities is becoming more and more dense. In many parts of the world, many metropolises experience urban phenomena called urban sprawl. There are more and more tall and high-rise buildings, because cities are like a magnet and are invariably attracting more people. The first skyscrapers of Manhattan were once unique, but today the race for tall buildings can be observed in the countries of the Middle and Far East. Urban public space has gradually become more stratified over the decades and is now developing above the ground. Vertical gardens are being built and public space is being introduced into buildings [1]. Greenery systems in architectural design are an important element of many modern projects in the world. They are a necessity when developing large metropolises, they compensate for the loss of biologically active areas, and reduce the outflow of rainwater to the sewerage system and the cost of building exploitation.

Covering the walls of a building with greenery has a potentially greater environmental impact than a green roof, since the surface of a building's walls is always larger than its roof area. A vertical garden not only affects the changing appearance of the building with the seasons, but also builds a microclimate, produces oxygen, absorbs CO2 and captures particles of pollution.
However, vertical gardens in buildings are not the first attempt of architecture towards ecology and greenery. The concept of garden cities has been known since the 19th century. According to its principles, city villas and apartment houses were built among trees and parks. The development of vertical gardens began with the presentation of Patric Blanc at the International Garden Festival in Chaumont-sur-Loire (France) in 1994. The presented structure, in the form of a wall covered with plants, aroused the interest of architects, and finally resulted in cooperation. Numerous ecological green designs were implemented by Jean Nouvel, Jacques Herzog and Pierre de Meuron.

Nowadays, plants are becoming an appropriate façade material in the creation of architecture. Their use is planned and dedicated to achieving both a specific aesthetic and ecological effect. The main problem is the planting of such a species to form a biotope, which, as in the case of the Bosco Verticale buildings project (Milan), Nanjing Tower (Nanjing), One Central Park (Sydney), Oasia Hotel (Singapore) or Beirut Terraces, requires huge precision at the design and execution stage. Currently, one of the most important figures in the world of architecture is the Italian architect Stefano Boeri, who creates vertical gardens in designed public buildings, including high-rise buildings. He is the author of the Bosco Verticale towers in Milan and the Nanjing Tower in Nanjing, as well as the designer of the Tower of cedars in Lausanne, the Mountain Forest Hotel in Guizhou and the green city of Liuzhou.

2. Green walls and living walls
With the development of green façade technology, various systems have appeared, which can generally be divided into green walls and living walls [2].

Green walls are systems where plants that are rooted in soil grow up a vertical surface and which have different systems for fixing plants to the building façade. Direct green walls are characterized by being directly attached to the wall. Intermediate systems contain a support structure for vegetation. In this case, the structural system consists of steel or composite trusses attached to the façade of the building, where the located vegetation is supported by horizontal, vertical and diagonal elements. Intermediate greening systems include continuous and modular solutions. Continuous guide bars are based on a single supporting structure that directs the development of plants along the entire surface. Green walls with modular trusses are similar construction solutions, but are made up of the installation of several modular elements located along the surface.

Living walls are an innovative form of wall claddings that appeared in order to cover large surfaces. As a result, the effect of more balanced plant growth on the surface of the walls was obtained. Living walls can be divided into continuous or modular forms. Continuous forms use light and permeable screens in which the plants are inserted individually. Modular forms contain elements of a specific size, which include diversified vegetation, and are based on a special structure or are fixed directly on a vertical surface. Living wall systems constructed of modular panels contain soil or other artificial media necessary for plant growth, and can be in the form of boxes, a foam system, or geotextile and mineral wool. The name of vertical gardens derives from the category of continuous living walls, which was first used in 1994 by the French botanist Patric Blanc.

The concept of vertical gardens in the form of green façades of buildings is now a trend of sustainable design, in which the ecological façade material offers an unlimited number of patterns and colors that change both during the day and in different seasons. To maintain a vertical garden on an artificial wall in a city, and at the same time ensure the safety of the building, it is necessary to make a supporting structure and to plan irrigation and nutrition systems. Each of the layers of a vertical garden can be formed in any shape. The supporting structure is usually in the form of a light metal frame suspended on the wall of the building. The waterproof layer is a standard PVC sheet and not only protects against water, but also ensures the rigidity of the entire structure. As a substrate on which plants can take root, a thick layer of felt is usually used. The felt made of polyamide is resistant to biodegradation and also ensures the retention and distribution of water and microelements. The irrigation system ensures a continuous water cycle and starts from the top of the wall.
3. Selected examples of high-rise buildings with vertical gardens

3.1. Bosco Verticale Tower E (Milan, Italy. 115.9 m)

The Bosco Verticale Towers D and E in Milan, designed by the Italian architect Stefan Boeri, provide support for one of the most intense green façades ever made [3,4]. The combination of its structure, safety, irrigation system and sophisticated selection of plants, with their location in all directions, enables the design of this building to be the most innovative design to date of a high-rise building. It can also be said to have introduced new standards for sustainable housing. The designer's main goal was to counteract the growing air pollution in Milan. As a new model of urban revitalization, the design creates gardens on terraces up to the 27th floor. Bosco Verticales are two residential buildings with a height of 115.5 m (E) and 85 m (D), which are characterized by the presence of dense vegetation along their external façade, figure 1. The vegetation includes about 20,000 species, including about 700 trees with a height of up to 6 m. All the plants have their roots in containers that are directly available from each apartment. Acting as an extension of the external façade, the plants are a filter between the interior of the building and the urban environment, producing oxygen and humidity, and also absorbing CO2.

The load-bearing structure of building E is a reinforced concrete slab-pillar with a central core, formed by 13 columns (80 x 120 cm) that are located on the perimeter of each floor with unsupported corners, figure 2. The core contains 2 staircases, 3 elevator shafts and 5 channels for mechanical, electrical and hydraulic systems. The load-bearing structure of the floor slabs and cantilever terraces is made of prestressed concrete with a thickness of 28 cm. The depth of the cantilever terraces is 3.3 m. Terrace profiles are repeated every six floors, while plant containers have a variable arrangement. The required weight, which acts on the terrace, was calculated for the deepest containers with high trees that are installed every 3 m, as well as for medium trees that are installed in the remaining spaces between the high ones. Trees generate a significant part of the loads, not because of their self-weight, but instead due to the action of wind that transfers to the building structure. For this reason, and in order to check
whether the trees will not fall over as a result of the impact of the wind, the building model was tested in an aerodynamic tunnel. Trees qualified as being high or medium in height are secured by a special security system in the form of textile straps attached to the slab floor. In addition to green plants, deciduous species were also planted, due to which the façade of the building changes color along with the changing seasons. Beech trees, yellow acacias, oaks, maples, ash trees, ferns and ivy decorate all four exterior walls of both towers.

In 2014, the Bosco Verticale towers were awarded as being the most beautiful and innovative high-rise buildings in the world.

![Diagram of Bosco Verticale Tower]

**Figure 2.** Bosco Verticale Tower. The layout of the vertical garden on the 6th floor

3.2. *Nanjing Tower 1, Tower 2 (Nanjing, China, 200 m, 108 m)*

Nanjing Green Towers is a design of Stefan Boeri that is planned for implementation. It will have two high-rise buildings with vertical gardens, and will be built in the southern province of Jiangsu in China and be the first high-rise buildings of this kind in Asia, figure 3. The Nanjing Vertical Forest design is the third in the world, after Milan and Lausanne, to be implemented by Stefano Boeri Architects Studio involving a vertical urban forest [5]. Located in Nanjing, in the Pukou District, the two towers are supposed to have a similar vertical forest, but will be much higher than its predecessor Bosco Verticale in Milan. 600 tall trees and 200 medium trees from 27 local species are to be planted along the façade,
plus another 2,500 cascading plants and shrubs, which will cover an area of 4,500 m². The vertical forest is to contribute to the regeneration of local biodiversity and provide 18 tons of CO₂ absorption and produce about 16.5 tons of oxygen per year.

![Figure 3. Nanjing Vertical Forest Towers](image)

The taller building will be 200 m high and topped with a green lantern. It will have an office and educational function from floors 8 to 35. A museum, a green school of architecture and a private rooftop club are also planned. The second 108-meter high tower includes the Hyatt Hotel with 247 rooms and a rooftop swimming pool. Both buildings rise from a common 20-meter podium, which performs commercial, recreational and educational functions. An important element of the structural analysis of this design is the impact of wind on the plants and the terraces that support them. To ensure the safety and efficiency of the vertical forest in Nanjing, many configurations were tested. During the design process the wind load acting on the building's structure in its present environment, and also at a later stage of urban development of the city, was analyzed. This design was recognized by the World Economic Forum as a perfect example of a biophilic project that is not only meant to help deal with pollution, which has accompanied the rapid economic development of China, but also to improve sustainable development.

3.3. One Central Park East (Sydney, Australia, 110.6 m)
One Central Park (OCP) is an ecologically designed project by the French Ateliers Jean Nouvel and Urbis Pty Ltd as part of the reconstruction of the Carlton & United Brewery near Central Station in Sydney. The project includes two buildings: Central Park East (33 storeys) and Central Park West (16 storeys), which are connected by a five-storey podium [6]. The innovative two towers feature ground-breaking architectural elements including the Sky Garden green roof and Heliotstat, and also the highest green walls in the world, figure 4.
The load-bearing structure of building E is a reinforced concrete slab-column with a central core, in which there are stairwells, an elevator shaft and channels for mechanical, electrical and hydraulic
systems, figure 5. In the upper part of the Central Park East building, a horizontal structure of 320 reflecting panels with an area of 520 m² (Heliostat) was suspended to a steel frame on a 40 m cantilever. Sunlight penetrates the glass roof to the five-level podium, providing light to the plants that are planted on its roof. On the roof of the lower building, 42 heliostats (sunlight-tracking mirrors) redirect sunlight to 320 reflectors on a cantilever from a taller building, which then emit light into areas that would otherwise remain in constant shade.

Designed by botanist Dr. Patrick Blanc, the symbiotic and revolutionary living walls are based on his hydroponic system. The planted walls use Patrick Blanc’s Le Mur Vegetal system, interspersed in 23 various sized panels across the facades of the two towers. The concept of the One Central Park façade was to have gardens on an unprecedented scale. These included green walls and planting boxes that contained hundreds of plant species. The Watpac Structural design team had to design these aspects in order to build the façade safely. The only limitation was the plants themselves, with 350 different species of plants in the green walls. It was necessary to consider the problem of building dust and poor lighting, and a large number of plants were therefore stored off-site due to the fact that they need access to water and natural light. In total, the façade contains more than 85,000 plants. On the north, east and west sides, the façade is characterized by green walls with continuous strips of cutting plants and climbing vegetation. On the southern side, the vertical garden rises in a sequence of randomly scattered plants that form various patterns in the facade: in an individual scale - a variety of gardens, and in a global scale - a green shape. Designers put the main emphasis on carbon dioxide emissions.

Using two technologies: hydroponics and heliostat, the plants were designed so that they grow throughout the building to provide organic shading, and also so that direct sunlight is collected throughout the year for heating and lighting. Shading saves on cooling energy, while redirected sunlight is a year-round source of light for the building and an adjacent park. Shadow vegetation reduces energy consumption for cooling, while their leaves capture carbon dioxide, all of which make the building more energy-sustainable. The plants capture carbon dioxide, emit oxygen and also reflect less heat than traditional permanent shading.

On the building's façade a light installation designed by the artist Yann Kersale is installed, which after dark imitates the movement of shiny fireworks in the sky.

In 2014, One Central park building was awarded as "The Best Tall building in the World" from the Council for Tall Buildings and Urban Habitat.

3.4. Hotel Oasia Downtown (Singapore, 193,3 m)

Hotel Oasia Downtown is located in the central business district of Singapore, adjacent to the historic district of Tanjong Pagar. The building, which was designed by the local design studio WOHA Architects, is distinguished by its décor, which is a showcase of architecture and engineering in Singapore [7]. The skyscraper's interior, which uses modern functional solutions, was designed by Spanish interior designer Patricia Urquiola. The building has a cylindrical form, a height of 191 m and is characterized by a new typology of a tropical skyscraper with many terraces with gardens and vertical vegetation, figure 6.

Hotel Oasia Downtown was designed for multi-functions: office, hotel and club rooms. A total of 100 offices and 314 hotel rooms are located in the 27-storey building, along with four sky terraces on levels 6, 12, 21 and 27 that offer ample public space for recreation and social interactions throughout the tower.

The load-bearing structure is a reinforced concrete slab-column, with four cores located in the corners of the truncated square plan, figure 7. With the structural cores, which are located in the corners of the building, "sky terraces" enable a unique 360-degree view through the gardens to the city. This would not be possible with a typical centrally located core. By dividing the skyscraper into vertical segments, the sky terraces, together with the green façade, provide an ecological surface area of over 1000% in relation to the surrounding buildings. Sky terraces also serve as huge overhangs, directly shading the terrace below. The characteristic elements of the building are the atriums appearing on every sky terrace that have a height of 21 to 35 m. Each atrium achieves an approximate ratio of height to depth of 1:1,
providing a bright and airy environment during daylight. The external aluminium grid in five shades of red, which is attached to the façade of the building, allows the integration of various biological forms and the creation of a green cover. In addition, it also creates a contrast with the lush greenery and blue sky and enables the building to stand out among the numerous skyscrapers in the city center. The façade of the building occupies 25,000 m\(^2\) and includes a total of 21 species of vines planted in about 1800 glass fiber boxes (on each floor) inside an aluminium grid that has suitable pavements for easy maintenance. There are 33 species of plants in the building in total, including a wide range of locally grown trees and shrubs, among others holm oak, wild pear, Koelreuteria, ornamental apple and hawthorn.

**Figure 6.** Hotel Oasia Downtown: section

**Figure 7.** Hotel Oasia Downtown, plans: 1) floor 6\(^{th}\), 2) floors 7-11\(^{th}\)
Hotel Oasis Downtown was awarded Green Mark Certification by Singapore’s Building and Construction Authority. It also won a Green Good Design Award from the Chicago Athenaeum and the European Centre for Architecture Art Design and Urban Studies.

3.5. Beirut terraces (Beirut, Libanon, 121.5 m)
Beirut terraces is a residential tower with a height of 121.5 m, located in the central business district of Beirut. It was designed by the Swiss architectural studio Herzog & de Meuron Architekten as part of a new master plan that is developing around the St Georges Hotel [8]. Beirut terraces creates new concept of tall building, with vertical garden composed of thin platforms layered in a playful formation, figure 8. This design was inspired by the history of Lebanon and is related to the multilayered civilization. The building has 27 floors above-ground, 6 under-ground and is placed on a podium that occupies 65% of its area.

![Figure 8. Beirut Terraces](image)

There is a shopping and recreation part, with a spa on the ground floor. There are also 132 apartments and they take the form of large areas (figure 9), with a glass partition that separates the interior from the outside. There are also some plants that separate the terrace of the bedroom from the larger terrace of the residential part of the tower. The building has four different entrances with a hall and elevators, which serve no more than two apartments at once.

Beirut terraces has a column-slab reinforced concrete structure with a central core. The columns were designed on a grid of 14.7 meters. As a result, the walls of the apartments are not of a load-bearing structure and their arrangement is flexible. To guarantee the diversity of the building's body, the skyscraper consists of five floor modules, repeated in various combinations. The floor slabs are extended beyond the double glazed walls by at least 60 cm in order to create shade and terraces. The load-bearing columns are placed in the corners of the building to support overhangs, and glazed balustrades are placed along the edge.
The layered structure of the skyscraper is characterized by the extension or withdrawal of a residential part through a very diversified terrace system. As a result, each storey is unique with different variants of the functional distribution of apartments. The moderate Beirut climate in which this building was designed for favors a solution in which the internal and external spaces connect with each other, which means that the extensive terraces for most part of the year become living spaces. The vegetation proposal implements the concept of an existing urban plan. The idea of a green boulevard which connects the residential skyscraper with the surroundings was included in the design and realized vertically both inside and outside the building. The interaction of architecture and nature, which animates the spacious lobby around the central core, is repeated on balconies and terraces throughout the building. Vegetation on the terraces acts like a screen that not only provides shade, but also provides privacy for every apartment.

The building design took third place for the Best Futura Project at the 2013 MIPIM awards, and was recognized as the best un-built sustainable design.

**Figure 9. Beirut Terraces, plans: 1) floor 8th**

### 4. Conclusions

The environmental problems caused by urbanized cities are approaching a climax due to the lack of space to provide more parks and greenery. Unthinkable urbanization has led to the creation of a concrete jungle in many cities. This situation encourages the vertical propagation of greenery, which adds green areas without taking up additional surface area. It is also important that the concrete frame of a building would be one of many similar buildings if not for its original vertical garden. In recent years there has been a global increase in the construction of green high-rise buildings. Many different ideas have been implemented, such as "bioclimatic skyscrapers", "eco-skyscrapers" or "vertical landscapes", which are ideas related to greenery in a building's design. Although the presence of greenery in buildings is not a new concept, nowadays its share in urban built-up areas has substantially increased.

A vertical garden, also known as a green wall or living wall, is a self-sufficient garden connected to the outer or inner walls of a building. Plants receive water and nutrients using special irrigation systems installed on the building's structure. Buildings that have green walls or vegetation integrated with the façade are characterized by many beneficial factors. These benefits vary depending on many things, such as: geographical location, climate, building geometry, plant orientation and suspension systems. According to the CTBUH Technical Guide, Green Walls in High-Rise Buildings, benefits can be achieved on an urban or building scale. The urban scale includes a reduction of the UHI green house
effect, improvement of air quality, noise reduction, ensuring biodiversity and the obtaining of an aesthetic effect, which in turn has a positive psychological impact on residents. However, the benefits on the scale of the building include: improvement of energy efficiency, consisting in their ability to influence the heat transfer between the interior of the building and the external environment, and also the protection of the façade against ultraviolet radiation.

Finally, it can be stated that high-rise buildings designed as "vertical gardens" use space and urban resources more effectively, and at the same time, albeit with high economical costs, create a more user-friendly and habitable place. Ecological high-rise buildings with vertical gardens designed by eminent architects such as Jean Nouvel, Stefan Boeri, Jacques Herzog or Pierre de Meuron inspire other architects, designers and developers and raise an important subject for considering the problem of sustainable construction in the aspect of the use of green façades in the future.

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