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## Vertical Forest Engineering: Applications of Vertical Forests with Self-Growing Connections in High-Rise Buildings

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### ABSTRACT

*Living architecture is thriving. The integration of buildings with vegetation has become a necessity in many metropolitan areas of the world today, including Singapore, New York City, Shanghai and Milan, to name a few. It expands the potential of vertical and horizontal, exterior and interior, exposed and enclosed spaces in a building that can be used to accommodate plants. Green infrastructures have benefits both on urban and building scales. They can be categorized into green roofs and vertical greenery systems that can be divided further into green façade, green/living wall, green terraces, elevated forests and vertical forests. There are many design and planting considerations for architects, structural engineers and botanists when using living architectures to mimic natural systems, such as climatic and regional considerations, primary functions and design objectives, structural support systems, maintenance, irrigation and so on. Plants used for vertical greenery are more likely to be hardwood species to adjust solar radiation during cooling and heating periods, and also for aesthetic pleasure. Take Bosco Verticale, which is located in Milan, as an example to look into engineering methods when trees grow on balconies of high rise buildings. It could be concluded that planting restraint safety system and regular maintenance are necessary for trees growing in the sky. But the change of growing conditions causes various problems such as stability and growth of trees. Instead of using steel cages and bracings to prevent falling off of trees in the sky, the concept of self-growing connections is proposed to provide the stability of vertical forests. This paper is meant to generate awareness of the possibilities of the integration of greenery vertically with buildings, show application considerations, and inspire future developments in typologies and integration with forests.*

### 1. INTRODUCTION

Cities are getting bigger and denser while buildings are getting bigger and taller. There is a growing significance of environmental issues such as urban island effects and reduction of energy consumption which are relevant to dense urbanization.

While high-rise buildings as a typology have evolved to become predominant nowadays, there are several challenges to meet. One is that buildings should be more in tune with their locations in term of both sustainability and design (Wood, 2008). Another challenge is that buildings should minimize the usage of non-renewable energy, pollution, with increased comfort, health, and safety of people who live and work in them (Sheweka & Magdy, 2011). With increasing building height, it is challenging to provide a high-quality work environment with natural ventilation. Because of higher and irregular wind speeds, this leads to a closing-off and dislocation of their natural surroundings.

Vegetation plays an important role by its special properties with energy balance and human health in urban areas. The benefits of vegetation in buildings are similar to ordinary vegetation in cities. It has become an important new construction principle to increase the livability and sustainability of modern buildings both outdoor and indoor (Feng & Hewage, 2014). Positive climatic effects can be created by combining green cover on walls, roofs, and in open spaces in the vicinity of buildings (Wilmer, 1990). Indoor plants can provide comfort by means of purification (Wolverton & Wolverton, 1993), humidification and psychological relaxation (Raji, Tenpierik, & van den Dobbelsteen, 2015), and indoor greening technology such as indoor vertical green walls has been proved to be one effective way to improve indoor air quality (Wang, Er, & Abdul-Rahman, 2016). While comparing outdoor plants with blinds in buildings,

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plants create more effective shading performance than blinds, which should be considered as a way of construction with building envelope (Stec, van Paassen, & Maziarz, 2005).

In densely populated regions, where green areas are scarce and open ground space is limited, the concept of integrating nature with high rise buildings represents an innovative and sustainable opportunity for green infrastructure in cities (Medl, Stangl, & Florineth, 2017). Greening technology can protect building façades which are under permanent environmental influences such as sun and rain which may damage the facades and reduce their service life (Köhler, 2008). Roofs of buildings are suitable spaces to accommodate vegetation. At the same time, greening of walls of high-rise buildings can also be feasible since the difference between surface area of walls and roofs can reach roughly 20 times (Pérez, Coma, Martorell et al., 2014). Numerous countries in the world, such as USA (Susorova, Angulo, Bahrami et al., 2013), Italy (Giacomello, 2015) and Singapore (Yok, 2013) have shown great interests in green infrastructures. The technologies of green infrastructures extend the potential of horizontal and vertical, exterior and interior spaces in a building that can accommodate plants (Tan, Köhler, Peck et al., 2014).

In this study, an identification and a classification of vertical greenery systems are proposed. Then some recommendations are given for design considerations and planting strategies that should be studied in depth. Based on the system of vertical forests, an innovative concept of self-growing connections is proposed to provide reliability and stability to a vertical forest. In the end, this study gives an overview on current debates and state-of-the-art technologies as a basis for further development of vertical forest engineering.

## **2. GREEN INFRASTRUCTURE**

### **2.1. CLASSIFICATION**

Greenery can be inserted on buildings in many forms including horizontal and vertical, exterior and interior spaces. Green infrastructure can be considered to comprise all natural, semi-natural and artificial networks of multifunctional ecological systems within, around and between urban areas, at all spatial scales (Tzoulas, Korpela, Venn et al., 2007). But because of the diversity of disciplines, application contexts, methods, terminologies, purposes and valuation criteria, there is no consensus on a comprehensive classification for green infrastructure (Koc, Osmond, & Peters, 2017). In this study, green infrastructures are organized into two main categories: green roofs and elevated forests which are considered horizontal greenery and vertical greenery systems which include green façades, green/living walls, green terraces and vertical forests.

### **2.2. HORIZONTAL GREENERY**

Green roof is one of the earliest forms of green infrastructures. Green roofs can be defined as roofs with a vegetated surface and substrate which can be divided into intensive and extensive green roof depending on substrate depths, roof dimension and intensity of use. It can provide ecosystem services in urban areas, including improved storm-water management, better regulation of building temperatures, increased sound insulation (Dunnett & Kingsbury, 2008), reduces urban heat-island effects (Besir & Cuce, 2018), and increased urban wildlife habitat (Bass, Rowe, Oberndorfer et al., 2007). Its relative lightweight nature allows its use on many roofs without the need for structural strengthening and it has seen a surge in installations worldwide (Tan et al., 2014). Another form of horizontal greenery is elevated forests which refers to trees growing in the sheltered horizontal spaces which form into forests in the sky. While horizontal spaces provide accommodations for plants, vertical spaces offer more possibilities. Apart from the development on the horizontal surface, vertical spaces provide opportunities to integrate vegetation with buildings.

### **2.3. VERTICAL GREENERY SYSTEMS**

The vertical greenery system can be defined as structures that spread vegetation that may or may not be attached to a building façade or to an interior wall (Pérez-Urrestarazu, Fernández-Cañero, Franco-Salas et al., 2015). It is also named as vertical garden (Peck, Callaghan, Kuhn et al., 1999), green wall, vertical green and sky-rise greenery (Blanc & Lalot, 2008; Tan et al., 2014; Timur & Karaca, 2013). According to the strategies of development of vertical greenery systems, they can be categorized as green façade, green/living wall, green terraces, elevated and vertical forests (Marugg, 2018; Ottelé, 2011; Serra, Bianco, Candelari et al., 2017; Sheweka & Magdy, 2011) (see Figure 1). But there are some differences between the definitions in various fields. Within this study, the characteristics and definitions can be seen in Figure 1 and Table 1.

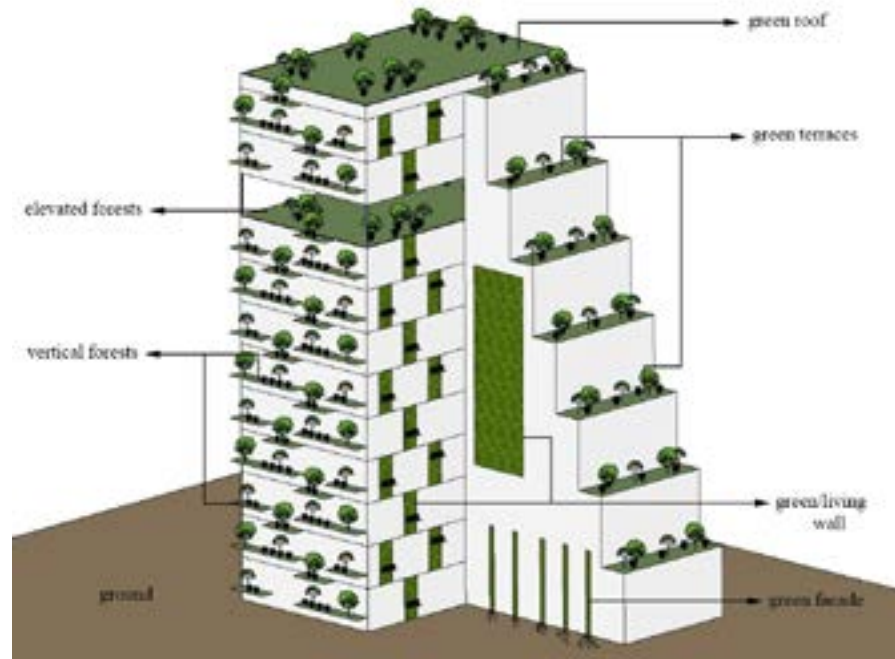


Figure 1 Classification

Table 1 Identification and classification of vertical greenery systems

Typologies	Plants	Characteristics
green façade	climbing plants	plants rooted on the ground and climbing on the façades of building themselves or with the support of other structures
green/living wall	modular plants or plants with hanging-down branches	supporting structures such as steel nets, modular rails and planter boxes that should be built on façades for hanging and placing plants
green terraces	short, medium and tall plants	planting in the planting media which is located on the horizontal terraces at different levels
elevated forest	trees	trees growing in the sheltered horizontal open spaces
vertical forest	trees	trees growing on cantilevering balconies

There are four main elements in the vertical greenery systems: plants, planting media such as substrate and containers, supporting systems which can hold plants, and irrigation systems (Wood, Bahrami, & Sfarik, 2014).

- **Green façade** refers to vegetation rooted on the ground, which makes use of either the wall itself for climbing (traditional direct systems) or independent supporting systems, such as trellis, wires, cables or meshes (double-skin indirect system) affixed to walls (Fernández-Cañero, Pérez Urrestarazu, & Perini, 2018).
- **Green or living walls** have been made using geotextile, pots, panels, boxes or modular nets where pre-cultivated vegetation has been planted and subsequently suspended and fixed to a larger vertical structure (Bartasaghi Koc, Osmond, & Peters, 2017). Living walls demand more complex constructions and imply higher installation and maintenance costs in comparison to green façades (Dunnett & Kingsbury, 2008).
- **Green terraces** are defined as plants growing on the horizontal terraces, which are built on different heights and levels.
- **Vertical forest** means when using cantilevered balconies around the envelop of a building to act as an accommodation for trees to grow, this group of trees is formed into vertical forests.

Vertical forest engineering is a relatively new field for architects, botanists and structural engineers to study deeper with respect to plant and tree species, nutrition and growth conditions (e.g. root system development) as well as engineering aspects with regard to wind loads, earthquake, tree stability and development of these over time.

### 3. BENEFITS

#### 3.1. ENVIRONMENTAL BENEFITS

Integration nature with buildings has become a necessary for buildings in densely populated urban areas. It is widely admitted that the proper arrangement of plants around buildings not only has psychological effects but also improves unfavorable microclimatic conditions around these buildings (Hoyano, 1988). Advantages of vertical greenery systems relate to environmental practices, economic and social benefits.

Regarding to environmental benefits, many studies have shown that using the technologies of vertical greenery systems can effectively mitigate the urban island effects. Because vegetation provides shading and evapotranspiration services that cool and regulate surface and atmospheric temperatures (Price, Jones, & Jefferson, 2015). Vegetation has the capacity of evapotranspiration. By evapotranspiration, large amounts of solar radiation can be converted into latent heat, which prevents temperature to rise rapidly during the day. With the increase of wind speed, evapotranspiration of vegetation increases too. Consequently, an efficient way to increase the evapotranspiration surface area in big cities is to cover buildings with vegetative greenery (Takakura, Kitade, & Goto, 2000). This can also be basically explained by decreasing wall temperature depending on variation of the effect of the wind on buildings, thermal insulation impact of vegetation and growth substrate (Besir & Cuce, 2018).

##### 3.1.1. WIND BARRIER

Wind speed and air temperature grow with increasing building height. Water vapor pressure is reduced by the combination of higher wind speed and higher air temperature. When evaluating the thermal performance of building façades, wind effect is one of the most notable factors which should be taken into consideration (Besir & Cuce, 2018).

The wind barrier effect refers to the capacity of the vertical green system, plants and support structure to modify direct wind effect over the building façade (Pérez et al., 2014). By affecting the wind speed with plants around building vertical spaces, a reduction of exterior wall temperature can be reached. According to a study by Perini et al. (2011) found that the wind speed within the foliage decreases nearly 0.43 m/s in comparison to 10cm distance from a bare wall and the wind speed inside vegetation is found to be close to zero. Franco et al. (2012) used wind tunnel test to evaluate the water volume retained, pressure drop, saturation efficiency and water consumption for three types of synthetic substrates used in active living walls to give recommendations for further research. By changing wind direction and wind speed with a vertical greenery system, the energy performance of the building could be optimized.

##### 3.1.2. SHADING EFFECT

Vegetation could provide direct shade to buildings and protect them from direct solar radiation. At the same time, it can absorb solar radiation for photosynthesis and evapotranspiration, therefore this can reduce solar reflection and re-radiation to atmosphere (Perini, Ottelé, Haas et al., 2013b; Sunakorn & Yimprayoon, 2011). Leaf area index is an important factor to provide energy saving through evapotranspiration and solar shading. Wong et al. (2009) conducted experiments on vertical greenery systems and found an equation showing that shading coefficient has a linear correlation with the leaf area index. However, shading effect may have both positive and negative effects depending on cooling and heating seasons. In summer seasons, plant canopies strategically integrated to building façades can act as sun screen devices to filter solar radiation and air with high temperature (Ip, Lam, & Miller, 2010). When using perennial plants both cooling and heating periods influenced by plant coverage whereas using deciduous plants only the cooling period is affected since the solar radiation will pass during the heating period (leafless period) (Pérez et al., 2014). During the summer months, vertical greenery systems would have the twofold effect of reducing incoming solar energy into the interior through shading and reducing heat flow into the building (Wong, Kwang Tan, Chen et al., 2010). Studies have shown that with proper and appropriate design and selection strategies of plants in vertical greenery systems, the positive effect of shading is obviously higher than negative effect, which can improve the energy performance of high-rise buildings (Marugg, 2018; Raji et al., 2015). In other words, to make full use of advantages of vertical greenery systems, the planting strategy is needed to take into consideration when vertical greenery system is applied.

### 3.1.3. THERMAL INSULATION

Vertical greenery systems recognize vegetation as having a larger impact in heat reduction when compared to artificial cooling (Price et al., 2015). The use of climbing plants and other vegetation types as a part of building enclosures has been shown to improve facade thermal performance during summer in Chicago (Susorova, Azimi, & Stephens, 2014). By evapotranspiration of vegetation, Besir and Cuce (2018) found that the external surface temperature of vertical greenery systems reduce in the range of 3.7 to 11.3°C while increasing the percentage of foliage in the system between 13% and 54%. Reductions in external surface temperatures of the building façades were considerable in warm temperate climate, ranging from 12 to 20.8°C in the summer period and 5 to 16°C in autumn (Pérez et al., 2014). Cuce (2017) studied green walls with about 10cm thick *Hedera helix* in sunny sky conditions of temperate climates like Nottingham. Results revealed that an average of 2.5°C reduction in internal wall temperature can be achieved. A case study in Hong Kong found that vertical greenery wall saved as much as 16% of the electricity consumption for air-conditioning in August and September with typical daily temperatures of 25 to 30°C (Pan & Chu, 2016). Inside urban canyons, results showed that the wind direction does not have any significant effect on temperature decreases due to vegetation (Alexandri & Jones, 2008). In the tropical climate, a study pointed out a reduction of surface temperature of building façades by a maximum of more than 11°C in the wall surface temperature on clear days (Wong, Kwang Tan, Chen, et al., 2010). Experiments on investigating the energy behavior on buildings in a Mediterranean temperate climate were conducted by Mazzali et al. (2013). The results showed that during sunny days, differences in temperature between the bare wall and the covered wall range from 12°C to 20°C. In different light conditions, the leaf orientation varies and leave of plants move. Based on TLiDAR, a movement parameterization of leaf can be quantified (Herrero-Huerta, Lindenbergh, & Gard, 2018). The thermal benefits of vertical greenery systems highly depend on vegetation intensity and its orientation with respect to the sun, possible intermediate air layers and plant characteristics such as growth rate, coverage, height, leaf area index and substrate thickness.

### 3.1.4. MISCELLANEOUS

Apart from that, acoustic performance of vertical greenery systems has been proven well at low to middle frequencies due to the absorbing effect of substrate while a smaller attenuation is observed at high frequencies due to scattering from greenery (Wong, Kwang Tan, Tan et al., 2010).

Urban vegetation has been shown to improve air quality by increasing air flow (Dunnett & Kingsbury, 2008; Perini et al., 2011) and depositing dust (Perini, Ottelé, Giulini et al., 2017). The air quality improvement due to vegetation is related to the absorption of fine dust particles and the uptake of gaseous pollutants (Perini, Ottelé, Haas et al., 2013a).

Vertical greening systems are especially important in dense urban areas as they create a habitat for urban plants and native wildlife by supporting biodiversity (Francis & Lorimer, 2011; Perini et al., 2013a). The benefits of biodiversity for human wellbeing are generally determined by the diversity of habitats and species in and around urban areas (Loreau, Naeem, Inchausti et al., 2001). However, biodiversity in sky gardens may not be as high as that at ground level, because of the thinner depth of soil, and more severe living environment on roofs and podiums such as higher temperature and stronger wind (Tian & Jim, 2011).

### 3.2. SOCIAL BENEFITS

Plants give beauty unstintingly and remains steadfast. It is known that people are more likely to suffer from a range of medical and mental health problems if they are living in areas without green nature. By providing a more comfortable living and working environment, it has also been proved that visual and physical contacts with plants can result in direct health benefits. Plants can generate restorative effects leading to decreased stress and improve work productivity (Sheweka & Magdy, 2011). Interacting with green plants regularly has a positive impact on human wellbeing.

### 3.3. ECONOMIC BENEFITS

By changing the energy performance of buildings with vertical greenery systems, energy saving is one among multiple benefits that a greenery system can offer to buildings (Coma, Pérez, de Gracia et al., 2017; Raji et al., 2015). The energy performance of a building in terms of the building envelope can be described as minimizing energy requirements for heating and cooling owing to the structural properties of the envelope (Besir & Cuce, 2018). The energy loss as a crucial issue for energy performance entirely depends on building age and type, climate, the materials of a building envelop, dweller behavior and geographic location. Irradiance reductions due to plants can reduce energy use for space cooling, and increase energy use for space heating. Plant canopies that shade buildings move the active heat absorbing surface from the building envelop to leaves (McPherson, Herrington, & Heisler, 1988).

In wet and cold climates in Hunan Province in China, an energy saving rate of 18% was achieved during the heating experiment owing to the extra thermal insulation provided by the vertical greening system (Xing, Hao, Lin et al., 2019). But planting strategies have adverse and beneficial effects on building energy performance. For energy effectiveness, tree arrangements provide shade, for instance, in Hong Kong primarily for east and west walls and roofs providing wind protection from the direction of prevailing winter winds, and this arrangement may vary depending on regions.

Because of a lack of technical information, maintenance instructions, and information on plants suitable for vertical greenery system locally, the adoption of vertical greenery systems is hindered. Similarly, the lack of awareness of long term economic benefits for building owners. Also grants and subsidies of the new system should also be considered for implementation. Economic benefits may be obtained by lower heating costs, reduction of air and noise pollution, improvement of human wellbeing by closure to nature which is a potential economic benefit, but may be negatively influenced by increased building and greenery maintenance costs during service life, and higher upfront costs for construction as structural detailing for cantilevering balconies with soil provisions may be more complex.

In general, the main benefits connected to vertical greenery systems include environmental, economic, and social aspects on both building and urban scales. But it also reflects that there is still a long way to go for the application of vertical forests.

#### 4. PLANTING STRATEGIES

The species used in outdoor living walls vary to a great extent, depending on the location, on the exposure to the sun and wind and on the height of the building (Pérez-Urrestarazu, Fernández-Cañero, Franco-Salas et al., 2015). There are some factors that can influence the growth of vegetation. These can be moisture stress and severe drought, extreme elevated temperatures, high light intensities and high wind speeds. They all increase the risk of desiccation and physical damage to vegetation and substrate (Dunnett & Kingsbury, 2008). Similarly, various plant physiological parameters such as leaf area index, average leaf dimension, and leaf absorptivity can improve facade thermal performance by reducing the exterior wall surface temperatures and heat flux through the façade (Susorova et al., 2013). For green façades, the number of useable plant species in the tropical area is between 300 and 500 climber species. This is around 10 times than in Europe (Köhler, 2008). Selection of suitable plant species depend upon many factors such as climatic conditions, building and plant orientation, wind effect, type of the soil, characteristics of container, requirement of water and nutrient, neighboring plant materials and preferred visual effect. Native plants should be given priority in selecting plant species as they are well adapted to local weather condition (Dahanayake & Chow, 2015). Strategies for selecting the most suitable plants are given in Table 2.

Table 2 Plants selection

Considerations	Strategies
plant arrangement	climatic consideration, orientation, wind effect, trees anchorage and fall off protection
plant species	aesthetic appreciation, foliage, density, growth rate, tolerance of high height condition maintenance and repair activities
planting media	properties such as thickness, moisture content and density
maintenance and inspection	pruning, weeding, watering, fertilization, plant replacement
irrigation and drainage system	accessible and well equipped for regular watering, water consumption waterproofing work

By combining engineered structures and botanical technologies, planting designs for cold climates preferably should reduce winter winds and provide solar access to south and east walls. For temperate climates, vegetation should be able to avoid blocking summer winds. In hot climates, high-branching shade trees and low ground covers should be used to promote both shade and wind (McPherson et al., 1988). However, some trade-off discussions can also be identified. For instance, from a structural viewpoint it would be advantageous to have the thickness of substrate as small as possible for weight reduction, but plants may grow less well and can require soil layers that are sufficiently thick to grow healthy in the long run. Similarly, with higher elevation it might become more advantageous to use low plants, reducing the cooling capacity of vertical forests.

## 5. DESIGN CONSIDERATIONS

As vertical greenery systems are relatively new applications in construction, there seem to be a lack of standard technical guidelines and maintenance specifications (Köhler, 2008; Tian & Jim, 2011). Singapore's Design for Safety for Rooftop Greenery (Parks, 2012) provides the only recommended guidelines for worker safety with a focus on design. During phases of design, installation and maintenance, many factors need to be taken into consideration before any decisions are taken, dealing with architectural and structural design, plant and environmental aspect.

### 5.1. DESIGN PHASE

During design phase, designers should take into consideration of many aspects including a suitable planting strategy, a sustainable material choice, the environmental impact, the interaction between the growing medium and vegetation (Perini et al., 2013a). Designers also should consider that the mechanical performance which might need to be characterized with technological support in the laboratory. An evaluation of the biometric parameters of the plants is also important. By analyzing the energy performance of buildings such as thermal behavior and acoustic performance with various vertical greenery systems, the most suitable one should also take local conditions into consideration. Before construction, technological issues that should be looked at are as follows.

- Making comparisons between different planting options according to structural performance of high-rise buildings, including additional loads by plants, the substrate and influences from extreme weather conditions;
- Applying proper ways of structural supports to prevent plants from falling down;
- Studying the influence of integrating greenery systems on energy saving for buildings ;
- Taking accessibility for regular and proper irrigation and maintenance activities into consideration;
- Checking whether a life cycle analysis (Perini et al., 2013a) can provide insights into an integral balance and discuss on cost effectiveness of different greening systems.

In order to optimize and balance all aspects involved, a multidisciplinary approach is needed and people from different fields should be joined together to make decisions during the early design phase.

### 5.2. INSTALLATION PHASE

Vertical greenery systems need to be designed in such a way that workers are able to maintain, re-plant, and provide overall care for the plants, which should be able to get free access to systems and avoid damage or fall off (Behm & Choon Hock, 2012). Vertical greenery systems present more potential access and fall protection issues compared to the rooftop greenery. Vegetation hanging over the edge of a building's roof (trees, creeper plants, etc.), presents additional safety challenges (Behm & Choon Hock, 2012). Such challenges will be considerable to façade cleaning teams.

Therefore, fall prevention and protection should be provided with special considerations for ledges. For vertical plants above ground level on roofs, terraces, and other upper surfaces, the height of the greenery should not exceed its horizontal distance from the roof edge or top of parapet unless fall protection measures are provided. In other words, the greenery should be set back from the edge of the building so that if equipment fails or a fall occurs, the distance is limited (Behm & Choon Hock, 2012). When a greenery system is designed onto building ledges, both fall protection and safe access options must be provided and consequently considered in the design phase when planning installation and maintenance.



### 5.3. MAINTENANCE PHASE

An optimal system will provide benefits with respect to human comfort and environmental impact with less additional maintenance costs. While living plants bring life to a building, they also add to the risk of failure through death of plants, an unsuccessful installation will cause additional costs of rectification. On the other hand, poor growing and dying as well as distorted plants will create an unsightly view that can affect the image of the building. However, there will be a trade-off between extra maintenance costs compared to a traditional building. With precise design and successful installation, improved environmental impact, jobs for maintenance workers and ecological services and improvement of social wellbeing have great values for buildings and societies in the long term.

## 6. VERTICAL FORESTS

An appropriate selection of tree species and a proper placement of trees around buildings are important to improve benefits of trees on reducing building energy use. The presence of trees acts as a barrier and blocks the thermal radiation emitted by the surface of the building façade (Berry, Livesley, & Aye, 2013). Trees can reduce external solar irradiance loads when they are close enough and tall enough to shade the majority of the wall (Berry et al., 2013). The characteristics of vertical forests include tree height, locations and spacing between the trees (both horizontal and vertical), distance between tree and the hard building envelope, canopy density and tree species. There are two cases (Table 3) collected where vertical forests have been applied as a way of improving the quality of high-rise buildings (Blanc & Lalot, 2008; Giacomello, 2015). All the plants and tree species growing on balconies of Bosco Verticale are selected according to the context, its climate conditions, orientation, solar exposition and height, which is shown in Table 3.

Table 3 Characteristics of cases

Cases	Pictures	Tree Species	Location and containers
Bosco Verticale Milan, Italy (Giacomello, 2015)		Acer Campestre Fagus Sylvatica Mafnolia Stellata Quercus Ilex Prunus Subhirtella Laburnum Alpinum (3-6-9 m high)	four sides of the envelop, around 1-meter-deep planter boxes with restraint systems to prevent fall off
Newton Suites Singapore (Blanc & Lalot, 2008)		Plumeria Palm trees	north and south sides with 900mm deep planter boxes

As for Bosco Verticale, small-scale wind load assessment was carried out using wind tunnel test to understand the aerodynamic and structural performance (Argentini, Fossati, & Muggiasca, 2010). Full-scale trees were investigated at a large open-jet facility in a local-effect study to account for the wind-tree interaction. Results show that at relatively high wind speeds the load coefficients tend to be reduced, limiting the wind loads on trees (Mousaad ALY, Fossati, Muggiasca et al., 2013). Trees planted on the balconies of Bosco Verticale classified as “large” and “medium” are secured to the structure of the terraces by means of temporary, basic and redundant binds. As is known, trees grow on the ground and their root systems develop freely, preventing trees from turning over in high winds. This change of growing conditions will have an influence on the development of root systems as they are restraint within the containers on the cantilever balconies.



Figure 2 Trees in the corner (Giacomello, 2015)



Figure 3 Growth of trees



Figure 4 A tree with different dense branches



Figure 5 Trees with different dense foliage

By observing trees (Figure 2-6) in Bosco Verticale, there are several aspects that need to pay attention to:

- It is observed that the orientation of branches and density of foliage are different between four sides of buildings due to the phototropism of the trees.
- If trees are applied to a horizontal forces frequently, it is likely that they grow with bended shape, which means trees that is under the effect of wind, especially for trees at corners and high levels will not grow straight vertically.
- With the development of time, trees grows both above and in ground. When the uprooting resistance of roots system ( $F_{wind} > F_{res}$ ,  $M_{wind} > M_{res}$ ) is not sufficient, it may lead to stability problems(Figure 6).

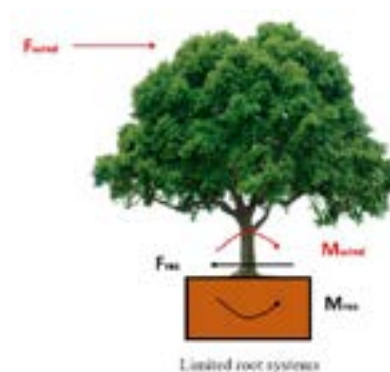


Figure 6 Stability of a single tree

Instead of using steel bracings and cages to hold trees for stability, self-growing connections between multiple trees is a possible way to provide the sufficient stability and resistance. Trees are growing organisms that can be manipulated in a natural way to grow into structures that can be useful in the built environment. The use of trees as structural

elements is possible for tree houses, where they act as a support structure (Nelson, 1997; Nuijten, 2011). Within the framework of a Building with Nature program, a self-growing tree structure has been created by the research group Biobased Structures and Materials of the Faculty of Civil Engineering and Geosciences of TU Delft, in cooperation with the Botanical Garden of the university. The structure is a study object that has been growing over the last 9 years. The trees are planted in such a way that young branches can be tied together at an early stage. Having tied branches together with a flexible tape, the trees are now interconnected by these naturally grown nodes (Figure 7,8), forming a structural entity by itself. In the Botanical Garden, the trees will be able to support a look-out platform within a couple of years. The nodes are the connections in natural tree structures that ensure the stability of a structural tree network. The advantages that are envisaged are a reduced need of tying the trees to the main structure, and reducing the effect of high wind loads on individual trees, avoiding excessive tree deformations. Three different node types are identified as shown in Figure 9. Each branch will probably retain its own biological and physiological structures but improved mechanical strength and stiffness will be created. The structure is the starting point for research into the internal structure of the nodes in order to address biological growth, structural performance of both trees and nodes, and the future development of such structures for use in the built environment, vertical forests and urban forests in particular (Borská, 2018).



Figure 7 Crosswise connection



Figure 8 parallel-surface connection



Figure 9 Typical nodes for interconnected trees: Three natural node types are studied: parallel-surface, crosswise and parallel-pith (Nuijten, 2011)

By using self-growing connections within vertical forests, it is possible to keep trees stable and less deformed as a result of high wind loads. The trees will grow more naturally shaped, effectively making the vertical forest more appealing.

## 7. CONCLUSIONS AND OUTLOOK

Classified types of vertical and horizontal greenery with definitions are given in this study. Greenery inserted on buildings can be organized into two main categories: horizontal greenery and vertical greenery systems. Green roofs and elevated forests are horizontal greenery which makes use of space horizontally. While integrating vegetation vertically is vertical greenery systems. They include green façade, green/living wall, green terraces and vertical forests. In this study, vertical forests mean when using cantilevered balconies around the envelop of a building to act as an accommodation for trees to grow. This group of trees is formed into vertical forests.

The main benefits related to vertical greenery systems include environmental, economic and social aspects. Environmentally, vertical greenery systems have a positive impact by wind barrier and shading effect, providing thermal insulation, reducing air pollution and noise. By getting closer to nature, human wellbeing can be improved.

Economic benefits may be obtained by lowering energy costs, reduction of air and noise pollution and improvement of living quality.

By combining engineered structures and botanical technologies, planting strategies and plants selection should be considered based on different regions usages.

For vertical forest engineering it is essential that criteria and design guidelines need to be developed including guidance for multi-criteria analyses. From design to maintenance phases, considerations for designers, engineers and relative workers are proposed.

The majority of recent studies mainly focuses on the evaluation of energy performance of buildings with vertical greenery systems. Fewer studies point out the importance of planting strategies. There is still a lack of knowledge on how to deploy high growing plants such as trees with high-rise buildings. From literature review, vertical greenery systems are primarily considered as a passive cooling option, and thermal studies need to compare it to other passive cooling options. Its potentials and magnitude of benefits, however, may not be the same across all seasons, climates and building designs (Hunter, Williams, Rayner et al., 2014; Pérez et al., 2014).

The success of a vertical greenery system relies partly on the ability to select suitable plant species that can maximize the capacity and performance of vertical greenery system. Plant selection, morphology, design and maintenance will differ from one climate to another. Advancement in research and technologies will aim to maximize benefits of application of vertical greenery system to suit a climate and building (Bustami, Belusko, Ward et al., 2018). There are very little research that has been focused on the analysis of the substrate or on the role of the growing media on root and plant growth (Serra et al., 2017). An extensive plant selection which may involve quality of foliage, color, texture, leaf shape, plant size, vigor, growth habits (Dunnett & Kingsbury, 2008) and its cost and effectiveness should be investigated.

Relevant guidelines and specifications for structural engineers should be developed with the effort from multidisciplinary approaches. Structural performance of buildings with vertical greenery systems should be looked into deeply especially for the wind performance of plants and high-rise buildings.

Vertical forest engineering with self-growing connections can be implied in the future. The mechanical properties of connections require further analyses but first inspections (Borská, 2018) indicate high stiffness and strength, similar to normal tree sections.

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