PLANTING GREEN TO THE SKY

vertical greening of existing residential building facades in Gothenburg

Bonan Yang

Chalmers University of Technology
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Chalmers University of Technology
Department of Architecture and Civil Engineering
Master's Programme of Architecture and Planning Beyond Sustainability (MPDSD)
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Examiner: Liane Thuvander

Figure 1.

Student background

Bonan Yang

1988	Born in Anshan, China		
2006-2011	Dalian University of Technology Bachelor Degree of Architecture		
2011-2016	China Architecture Design and Research Group Assistant Architect Architect		
2016-2018	Independent Architect		
2018-2020	Chalmers University of Technology Architecture - MSc.	90.0	ECTS
	Sustainable development and the design professions	7.5	ECTS
	Design and planning for social inclusion	22.5	ECTS
	Design systems	4.5	ECTS
	Light and color theory	3.0	ECTS
	Sustainable architectural design	22.5	ECTS
	Architecture Geometry	7.5	ECTS
	Building design lab	7.5	ECTS
	Sustainable building competition	15.0	ECTS

Abstract

The background of this thesis is based on the development and expansion of modern cities, especially in downtown areas, resulting in a large reduction of green lands and the decline of urban ecological environment. With the increasing density of buildings, architects could think about how to increase the greenery coverage of downtown areas by design, thereby improving the urban environment, which is the aim of this thesis. The design of the building-facade greening is the main object.

How to find suitable solutions of façade greening for existing residential buildings, under the climate and local context of Gothenburg, is the main research question for this thesis. These solutions focus on different types of facades, and should be in the principle of feasibility and adaptability, low cost and maintenance. The greenery projects could provide facade upgrading to the houses in both aesthetic and ecological ways.

The first section is about the studies on the context, like the influence, types, plants and maintenance of conventional façade greenery around the world, and the situation of climate, residential building and suitable plants in Gothenburg. The second part is to find greening strategies for different building conditions, like height, material, orientation, components, and think about how to reuse materials and rain to make the system more sustainable and low-cost. The third part is about greening design of three chosen facades in different conditions, which consists of their general greenery views, constructions, materials, details, suitable plants and maintenance.

As the result of this thesis, I design multiple methods of façade greening for different building conditions, by listing their adaption and suitable plants, showing their constructions, details and materials. These methods are utilized on the three chosen building facades, bringing the facades more beautiful and ecological appearances with green elements. In addition, these greenery methods are flexible, and they can bring more potentials of façade patterns, when the combination are different.

In greening projects, there are many parameters which have influence on the success and sustainability of the greenery system, such as climate, building conditions, plants, maintenance, constructing styles, and so on. Therefore, in the design, it is important for architects to have integrated and holistic analysis of all these parameters, thereby finding right solutions for different projects.

Keywords:
1. Vertical greenery design; 2. Residential-building facade regeneration;
3. Maintenance of plants & irrigation; 4. Recycled material; 5. Detail solutions

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Background

From the perspective of ecological composition, what are the main differences between cities and nature? Nature is mainly composed of animals(including human), plants, insects, minerals, water, sunlight, and air. In addition to water, sunlight, and air, cities today are mainly composed of people and minerals which are mainly in the form of glass, metal, and concrete, while the proportion of plants, animals and insects is very low. The increasing acceleration of urbanization is making today's cities farther and farther away from our ideal natural environment. Today, more and more people are concentrated into big cities to seek more job opportunities and better living conditions. As a result of this phenomenon, cities need more buildings, streets, and other infrastructure to meet the increasing demands caused by population growth. The original urban green-space was occupied by expanded buildings and streets, and the land left for green vegetation in the city became smaller and smaller.

Contrary to the reality, we actually need more green vegetation to improve our living environment and bring our cities back to the nature. Vegetation has a lot of benefits for the urban environment and human health. For example, plants can help purify the air, clean dust, absorb noise, increase humidity, store rainwater to control flood, absorb heat radiation and reduce the urban heat island effect, etc. In addition, green plants can make people feel happy, relaxed, and help protect eyesight, thereby reducing the stress, alienation, and apathy brought by modern industrial cities with metal and concrete.

People can not stop the development of cities, but what we can do is to find other ways to increase the green-coverage in cities. In today's tightening urban green space, developing vertical urban greenery is undoubtedly one of the most direct and effective methods to solve this problem.

Aim

In general, the aim of this thesis is to increase the greening rate of cities, especially in the downtown areas, by vertical greening on building facades, thereby improving the landscape of cities and relieving the decline of urban environment caused by city development and expansion.

In terms of the concrete design and methods, the purpose is to search suitable facade-greening methods for different conditions of residential buildings in Gothenburg, which has a large number of exsiting residences in the downtown area. These methods should be in a feasible, low-cost and sustainable way. For example, using recycled or natural materials, water-saving and effective irrigation system, simple and flexible constructions which do not impact buildings a lot. These plans could provide sustainable solutions in both aesthetic and ecological way to the house-upgrading in Gothenburg.

Research questions

How to find suitable design strategies of façade greening for a certain kind of building which is under a certain climate condition and local context, like under the situation of Gothenburg?

Sub-questions

1. How to identify and choose suitable plants for different types of façade greenery, local climates, and building surrounding conditions?
2. How to choose vertical greening methods for building facades in different heights, materials and styles?
3. How to design suitable and sustainable maintenance for different facades and greening methods to keep plants alive and get ideal façade effects?
4. How to design integrated greenery facades in a low-cost, low-maintenance and sustainable way?

Method

The study of this thesis consists of three phases, inventory part, strategy part, and design part.

In the inventory part, the content is about the studies on the conventional façade-greenings and the local context of Gothenburg. By studying on the websites of some famous façade-greening projects in different countries and a few scientific articles of vertical greenery, the general information about the influence, types, plants and maintenance of façade greenery has been summarized. As for the local context of Gothenburg, many photos were taken to record the residential building conditions, and the interviews of three local botanist, gardener and landscape architect help to find suitable plants for vertical greenery in Gothenburg. According to the statistics from a weather website, the climate feature of Gothenburg is got and listed.

In the strategy section, the main work is to find greening strategies for different building conditions and think about how to reuse materials and rain water to make the system more sustainable and low-cost. Based on the photos of residential buildings in Gothenburg, different building conditions, like orientation, height, façade material, component, maintenance and surroundings were listed, and it was analyzed how these different conditions impact the façade greenery. In the next step, the information of façade-greening products was studied, like climbing-aids and fixings, and irrigation items from some websites of relative companies. According to the information and some advices from a structure engineer, special attention was paid to what kinds of waste materials could be reused in the project and how to recycle rain water for irrigation system. At last, by analyzing the issues of reference living wall projects, strategies of a more flexible method were defined.

At last, the design part is about greening design of three chosen facades in different conditions, regarding their general greenery views, constructions, materials, details, suitable plants and maintenance. By building digital models and detail-section drawings, multiple greenery methods are designed, with certain constructions, details and materials. These methods are also utilized on the chosen facades following their unique conditions, and generating integrated green façade views.

Delimitations

1. The research item of this thesis is only about the façade greening regeneration of existing residential buildings in Gothenburg, not about other types of buildings, new-built residences, or the roof garden design.

Compared with most public buildings, the residences usually have unspectacular and simple facades. Therefore, most of them need facade-greening to upgrade their appearance more than those public ones. The number of new-built residences is very limited in Gothenburg, and it is much fewer than that of the existing ones. In terms of vertical greenery, facade greening is relatively a new aspect, and still needs more research and studies than the roof garden. In addition, the area of a building's facades is always much bigger than that of the roof, which means there are more potentials for facade greenery. As for enhancing the landscape of community and city, the plants on facades are also more visiable and effective than those on roofs.

2. Among all kinds of residential buildings, the medium-height residential buildings, with three to ten floors, are the researching objects in this thesis. There are no special greenery plans for small houses, rowhouses and high-rises in the thesis.

In Gothenburg, the small houses and rowhouses are normally located in suburb areas, which means they already have good and natural surroundings and in low-density areas. Therefore, these houses do not have a strong need of more plants. Those high residential houses with over ten floors are a minority group, they are not as common as the medium-height ones.

3. In terms of façade greening methods, only the common ones with low cost and maintenance are used for the design in this thesis. The high-tech methods, like vertical garden and vertical forest, are not suitable for a sustainable regeneration.

The high-tech greening always have high requirements of materials, constructions and maintenance, which means there will be more costs, labor or resources consumed in build and maintenance. This is not a sustainable way for building regeneration.

4. The thesis does not go deep into discussing the impacts of greenery facades on urban environment, physical properties of buildings, and people's mental and physical health.

There have already been so many articles and books talking about the greenry influence.

RESEARCH & ANALYSIS

Studies of literature and built references

Greenery influences on environment, buildings and people

Many studies have shown that green plants have many advantages for urban environments and buildings. At the same time, the greenery on building facades may also have some negative impacts on the buildings and the users. This part lists some typical effects which the plants may cause.

1. Positive effects

Plants can help to improve urban air quality, which is mainly about absorption of fine dust particles (PM) and uptake of gaseous pollutants, such as CO_2, NO_2 and SO_2. Plants use carbon dioxide for photosynthesis, and convert sulfur and nitrogen into inorganic salts [1, 2]. The fine dust particles, especially the tiny ones, like PM10 and PM2.5, fine particles with a diameter of 10(2.5) μm or less, which could cause damage to the human respiratory system, are mainly adhered to the outside of the vegetation parts.[3]

The urban heat island phenomenon is mainly caused by the amount of artificial hard surfaces, with high reflectivity, compared with natural land cover [4]. In terms of the artificial surfaces covered by vegetations, a large amount of solar radiation will be absorbed by green plants and used for photosynthesis, transpiration, evaporation and respiration, thereby reducing the degree of being heated of the hard surfaces.[5]

In warm and hot climates, plants covering the building surface can help reduce the surface temperature of the building, thereby improving the microclimate around the building, and effectively reducing the building's cooling energy consumption [6]. Field measurements, conducted in Germany, on a plant covered wall and a bare wall by Bartfelder and Köhler shows a temperature reduction at the green façade in arrange of 2-6 °C compared with the bare wall [7]. In addition, plants absorb solar radiation to promote transpiration and can also help increase humidity in the surrounding environment.

Some kinds of greenery on facades can also have positive influence on the thermal insulation properties of the building envelops. This comes to the thickness of the foliage (creating a stagnant air layer and shading the façade), water content, material properties and possible air cavities between the different layers. In addition, a study conducted by Perini et al [8] shows the potential of vertical green layers on reducing the wind velocity around building façades, thereby helping improve the thermal properties. This means that, in both warm and cold climates, building envelopes covered by plants have possibility to help save energy [9].

Plants covering building facades could have shading effects, which stop a large amount of UV light falling on building materials. Since UV light deteriorates the material and mechanical properties of coatings, paints, plastics, etc., plants can have a positive impact on the durability of buildings and reduce maintenance costs [9].

Plants also have possibilities of positive influences on human's mental and physical health. With a number of research studies illustrating that, greenery is widely recognized as therapeutic, for example, patients in hospital, who can see greenery outside the window, normally recover sooner than those without green views, and people who work in an environment with green plants feel less stressful than the ones in normal offices [9, 10].

2. Negative effects

Dead plants, and fallen leaves litter, may cause fire problems during the dry seasons. Therefore, dead or dry vegetation must be removed as part of regular maintenance. Fire resistance can also be increased by installing breaks in the vegetation. Evergreen climbers usually will not have fire issues, when dry leaf litter falls away cleanly and is removed during routine maintenance. And plants with regular irrigation will also not cause fire issues [11].

The lush-growing climbers on building facades may cause some impact on the components of building, like the open of windows and the use of balconies. Sometimes, failure may be due to a long-term problem that has gone undetected, such as blocked drains by tree roots. These issues could be solved by regular pruning and cleaning (Figure 2), or setting breaks outside windows [11].

Some plants' pollen could cause allergic issues to some people during the flowering season, and some plants have mild toxins. These problems can have an adverse effect on the users of the building or others. Therefore, the allergic and toxic plants should be avoid in façade greening [11] .

Green facades are attractive to insects, and the insects climbing on windows or entering indoor spaces will disturb people's daily lives. Installing invisible mesh (Figure 3) on windows is a good choice.

Figure 2. Regular pruning of green facade, clean the plants around windows

Figure 3. Adding invisible mesh inside windows

Common plant species for facade greening

In this part, some built projects were to research what kinds of plants are commonly used for vertical greening on building facades all over the world, in which conditions and greening methods they can work well, and the features of them. Typical types of plants are the followings:

1. Climbers (self-clinger) (Figure 4a)
A typical plant of this kind is Parthenocissus, and it can climb up on the wall directly without any supporting cables or meshes. Brick or stone facades with mortar is the ideal medium for climbing. Although its roots and stems can go into the gaps in the wall, it normally does not make damage to the constructions. This kind of plant is usually planted in the ground on the outside of walls, which could provide enough nutrition and water to make plants grow well. The plants will grow up and cover the wall as a kind of green façade. The growth height depends on different plants, maintenance and growing conditions, and some species can grow up to around 15 meters.

2. Climbers (twining or tendril) (Figure 4b)
A typical plant of this kind is Hedera helix, and it needs supporting systems to climb up. The common supportings are metal cables, or metal, wood, plastic meshes and trellis. Because the plants' roots or stems entangle or adsorb on supporting systems, they does not make any damage to the walls' construction. This kind of plant can be planted both in the ground and in planters with less soils, but normally, it grows higher and lusher in the ground than in planters. The growth height depends on different plants, maintenance and growing conditions, and some species can grow up to around 15 meters. It is common to see this kind of plant on buildings' outside walls, guardrails of balconies, flower stands and fences.

3. Hanging plants (Figure 4c)
There are many kinds of hanging plants in various categories, and when there is no supporting systems, some climbers will hang down. Lysimachia nummularia is a common one in Scandinavia region. The size of hanging plants usually range from 0.5 to 2 meters, and this plant is always putted in planters or small pots, which means it does not need much soil to keep growing well. By different arrangement of hanging plants, there are a variety of patterns, and a common one is the green curtain. Hanging plants could be found in different positions of buildings, on outside walls, on balconies or other platforms, outside windows, on eaves, on flower stands.

4. Herbaceous plants (Figure 4d)
Herbaceous plants are normally small sizes, with height under 0.6 meter, and planted in small pots or small planters. Without much soil, the weight of those pots or planters are light, and they can be easily hanged outside windows or putted on balconies. Herbaceous plants is a big family with all kinds of flowers and leaves, and some species are evergreen and even have flowers in winter.

5. Flowering shrubs (Figure 4e)
Flowering shrubs are similar with herbaceous plants in many aspects, but they are usually in larger sizes than herbaceous, which means they need more soil, larger pots, and they are heavier. In most projects, flowering shrubs are in big planters or growing-beds which are putted on certain platforms or balconies, and need more irrigation and nutrition supply to keep them growing. Therefore, the load-bearing ability, water-proofing layer, anti-root layer, irrigation system and nutrition supply need to be considering, when designing flowering shrubs on building facades.

6. Small trees (Figure 4f)
Small trees are the largest kind of plants in building vertical greening, and also the hardest ones to keep alive. In vertical greenery, they are always in the combination with flowering shrubs on certain balconies or platforms. With higher demands than flowering shrubs, the construction and maintenance system for small-tree planting always need special design.

Above all, among these six kinds of plants, the plant types 1 to 4 are more common in built references, and can be installed and maintained in easier ways. Flowering shrubs and small trees need special constructions with higher load-bearing ability, water-proofing system, anti-root system, drainage system, and special maintenance systems. It is better to think about these special requirements when starting to design a new building, instead of regenerating an existing construction.

Figure 4. Different plants on building facades
(a) Climbers(self-clinger)
(b) Climbers(twining or tendril)
(c) Hanging plants
(d) Herbaceous plants in small pots
(e) Flowering shrubs
(f) Small trees

Maintenance of plants and buildings

Maintenance is crucial to the living and good performance of plants on building facades, and good maintenance can guarantee the ideal design effect of greening. The maintenance of façade greenery includes multiple aspects, not only about plants, but also the support systems of plants, and the constructions and components of buildings. Generally speaking, suitable growth medium, irrigation and fertilizer are crucial factors of successful greenery. Moreover, pruning, removal of leaf litter and replacement of dead or ill plants are also important to a greening system. In this section, the information about vertical greening maintenance is from the book, Julie Francis, Gail Hall, Sue Murphy, John Rayner, 2014, A guide to green roofs, walls and facades, in Melbourne and Victoria, Australia.

1. Maintenance planning
A maintenance plan should include a clear description of:
maintenance objectives, created based on the design intent, or the landscaping or environmental objectives that were the basis for the roof, wall or facade development; performance targets, such as the time frame for complete coverage of an area by plants and foliage; responsibilities of various personnel involved in operating the building, outlining the type, scope, duration of task and occurrence; training requirements (such as Working at Heights certification) and safety equipment; resources available.

2. Growth medium
Generally, sandy loam topsoil in medium-moist, loose and well-drained condition is a kind of ideal growth medium for plants, both in outdoor ground and in containers. There are also some other kinds of growth medium on the market, which are usually for small pots and planters. Hydroponic plants should be planted in some artificial substrate, such as foam, felt, perlite and mineral wool. In addition, using what and how much substrate should depend on the features of plants, greening methods and expected effects. The density and volume of the substrate, and its weight after irrigation or rain, will have a burden on the support system, which should be considered before design. At last, in some conditions, growth medium need regular replenishment or replacement.

3. Irrigation
Water is a key point to the success of the façade greenery, and proper irrigation can guarantee the lush growth of plants. Generally, façade greenery planted in good quality soil outdoor does not need any additional artificial irrigation, but greenery in containers usually needs the automatic drip irrigation systems or manual irrigation. Hydroponic plants always require more and exact-controlled irrigation amount, and their growth environment needs to be monitored. Different plants have different demands of water, so it is better to choose the drought-tolerant plants for façade greening, in order to reduce the difficulty and cost of maintenance. In addition, irrigation amount also depends on local climate, for example, plants need more water when there is little rain for a long period or in hot summer.

4. Fertilizer
For vertical greenery, depending on various situations, choosing different fertilizing strategies. Façade greenery planted in good quality, sandy loam soil outdoor usually does not need any additional fertilizer. For plants in garden beds and containers, giving additional fertilizer once or twice per year is to supply nutrients and improve water retention. Controlled release fertilizer (CRF) is the most suitable choice for plants in containers. Hydroponic plants should choose nutrient liquid, and mix it into irrigation. If possible, undertaking soil testing of pH and electrical conductivity to help judge if there is enough nutrition for plants.

5. Common maintenance tasks

Some typical maintenance activities for facade greenery are outlined below in Table 1. These are intended as a general guide only: each site will have its own specific requirements and some listed will be more relevant and/or specific facade greening.

Maintenance Objective	Task
Maintain planting design	*Plant replacement, infill plantings*
Maintain plant growth	*Remove waste plant material (leaf litter, prunings, weeds), inspect for signs of pests or disease and treat as needed, make seasonal adjustments to irrigation volume and frequency as needed, ensure adequate nutrition levels for plants; inspect after severe weather events (e.g. wind or heat) to look for signs of stress*
Maintain climbing plants	*Annual or biannual pruning to maintain density and cover and to remove growth from fixtures (windows, drains). Rejuvenate to renovate habit and growth*
Rejuvenate climbing plants	*Vigorous pruning to renew stems and encourage new basal growth (every 5-7 years)*
Monitor plant performance	*Maintain records of plant health, vigour and coverage, pest and disease impact*
Maintain substrate	*Top-up of growing substrate may be required due to wind, rain or animal activity (check the depth of the growing substrate before any additions are made to ensure weight loadings are not exceeded)*
Maintain irrigation (and fertigation) systems	*Manually test and inspect the irrigation system regularly and monitor any automated systems (check volume of irrigation delivered, its frequency, substrate moisture content, and, for hydroponic green walls, nutrient levels in the water supply)*
Monitor plant nutrition	*aintain a log of fertiliser additions and records of pH and electrical conductivity values before and after addition of fertiliser*
Maintain non-vegetated zones	*Remove vegetation from perimeter zones and around other equipment and fixtures*
Maintain wind protection features	*Check the condition and fit of protection systems*
Maintain waterproofing	*Inspect flashings over waterproofing membrane terminations, inspect wall fabric for any damage from water, fertiliser or plants*
Maintain other hardscapes	*Clean or oil decking or furniture, inspect green wall or facade support systems for any loose attachments or fittings*

Table 1. Common maintenance tasks of vertical greenery

Climate of Gothenburg

Local climate has a key impact on what plants can survive and grow well in a certain region. Understanding the climate of a place could help architects to choose right plants for their projects and design suitable maintenance strategies. In this part, five main elements of the climate situation in Gothenburg are listed, and their influences on plant-growth are analyzed. All the statistics for Gothenburg weather are from https://weatherspark.com/y/71566/Average-Weather-in-Goteborg-Sweden-Year-Round, www.ladybug.tools/epwmap/, and the simulation of Grasshopper and Ladybug. The data are based on a statistical analysis of historical hourly weather reports and model reconstructions from January 1, 1980 to December 31, 2016 in Gothenburg.

1. Temperature

During a year, there are 5 months with average temperature between 10 to 20 degree, and 7 months from around 0 to 10 degree. The coldest days are in December, January and February, the low temperature could fall below 0 and even below -10. The warmest days are in June, July and August, the high temperature could climb up to over 25 degree. Therefore, according to the data, Gothenburg has a long and relatively cold winter, and a short and warm summer. Those plants which can be against cold weather and do not like hot weather are suitable for outdoor greening.

2. Cloud

In Gothenburg, during half of a year, mainly in autumn and winter, two thirds of the weather is cloudy and overcast, and even in spring and summer, only half of the days is sunny. According to the data, those plants which are shade-tolerant and do not need strong light, are suitable for outdoor greening.

3. Sun-hours

In Gothenburg, southern facade receive much more sun lights than others, and eastern facade always has a little more daylights than west. During half of the year, around summer, there are sun lights directly on the northern facade, and during May to July, the number is near to west and east. According to the data above, it is better to choose plants with different light needs for different facades, especially the northern one. However, due to direct sunlight, the plants on northern façade should like shade and are also light-tolerant.

4. Rain and snow

In Gothenburg, about one third of a year has rain or snow, and although there are less rain in spring, the number of rainy days is still near 30%. The snowing season of Gothenburg is from November to March, but compared with rainy days, the snowy days are still much less in these months. The amount of rain and snow is relatively even during the whole year, and spring is a litter drier. Although one third of days are rainy, the annual precipitation is not too high. The amount of snowfall is not much in winter. According to the data, the water situation is suitable for many plants, but those plants which like dry or very wet condition should not be chosen. The snow will have some bad influence on plants, so it is better to choose snow-tolerant plants if we want them to be green all the year.

5. Wind

In Gothenburg, the speed of wind is even all the year, around 14km/h, and the main wind comes from south in autumn and winter, from west in spring and summer. Therefore, the plants on south and west facades should have better wind and lodging resistance, smaller shapes, stronger roots.

Typical residential facades of Gothenburg

Different materials, components and sizes of facades will need different plants, greenery and maintenance strategies. In this part, studying in various kinds of built residential buildings in Gothenburg, to understand their constructions and features.

Facade materials:

1. Brick facades (Figure 5)
Brick is very common as a façade material in residential buildings in Gothenburg, and it could be found in both low and tall buildings. It could be the main material of a whole façade, a part of a façade or just used as some decorations. In Gothenburg, bricks have been used in building constructions for hundreds of years, and until now, they still act as an important role in many new projects. Red, yellow and brown are the most common colors of brick in Gothenburg, but in some projects, the brick facades were painted by other colors. As a façade material, brick is very durable. They normally do not need much maintenance or regeneration.

2. Concrete facades (Figure 6)
Concrete is not only common for load-bearing systems, but also common for building facades. Among the higher residential buildings of Gothenburg, the ones with concrete facades occupy a large part, especially the buildings of the Million Program during 1960s or 1970s. Those buildings normally have plain concrete or concrete with gravels and mortar as their facades. Nowadays, many new houses still use concrete as façade material, but usually painted with colors. It is hard to find concrete-façade houses before 1950s in Gothenburg. Concrete facades normally need maintenance or regeneration after a few decades to make it look new or keep good performance.

3. Metal facades (Figure 7)
Metal facades refer to using metal plates to cover the surfaces of buildings. In Gothenburg, there are not many residences with metal plates covering the whole façade, but colorful metal plates are commonly used on parts of a building façade, like rai-guard of balcony or the wall between two windows. Metal-façade houses mainly appeared during 1980s, and until now, many new buildings still like to use metal plates on parts of their surface. Metal plates are susceptible to rain and sunlight, which makes the plates look dirty and old after some years, so they need regeneration by few decades.

4. Foam facades (Figure 8)
Foam façade refers to the installation of a layer of thermal-insulation foam on surfaces of exterior wall, and coating it with paint and mortar outside as protect layer. In Gothenburg, this kind of material was used on residential buildings during 1990s, and the main purpose was the regeneration of old houses. The foam is not durable and has some problems, like being fragile and causing moist and mold issue. Therefore, in recent years, it has not been used on building surfaces of neither old houses nor new ones. This kind of façade needs relatively shorter regeneration cycles.

5. Wood facades (Figure 9)
In Gothenburg, wood is the main material of exterior walls in most small houses and rowhouses, but not common in other residences. Those houses with wood facades are mainly built between 1890s and 1930s. They are 3 or 4 storeys, and the ground floor has brick or stone exterior walls, the other floors are with wooden walls. Of course, a few new-built apartments have wood facades, but rarely in those medium or high ones. Wood is not as durable as brick and stone, so it needs maintenance, repairment or repaint by a period.

6. Fiber cement facades (Figure 10)
Similar with metal façades, fiber cement facades use fiber cement plates to cover the surfaces of buildings. This kind of building mainly appeared during 2010s, as a popular surface material used in the regeneration of old buildings, and also used in a lot of new projects. Various-colorful plates are used in both low and high houses. Fiber cement facades need maintenance and regeneration every few decades.

7. Stone facades (Figure 11)
Residential buildings with stone façade are not common in Gothenburg, and they are mainly concentrated in the downtown area in the classical style. In addition, most of them are not used as residence now.

Figure 5. Brick facade houses in Gothenburg

Figure 6. Concrete facade houses in Gothenburg

Figure 7. Metal facade houses in Gothenburg

Figure 8. Foam facade houses in Gothenburg

Figure 9. Wood facade houses in Gothenburg

Figure 10. Fiber cement facade houses in Gothenburg

Figure 11. Stone facade houses in Gothenburg

Facade components:

8. Windows (Figure 12)

The window opening-method and the relation between windows and walls will impact the greenery styles on facades. In Gothenburg, the windows of most residential buildings are similar in construction and material. The opening methods of windows are mainly top-hung window and casement window.

(a) (b) (c) (d) (e) (f) (g)

Figure 12. Window solutions for different facade materials
(a) Brick facade, (b) Concrete facade, (c) Metal facade, (d) Foam facade, (e) Wood facade, (f) Fiber cement facade, (g) Stone facade

9. Balconies (Figure 13)
The construction of balcony and the relation between balconies and walls will impact the greenery styles on facades. The constructions, materials and styles of balconies are almost the same in different residential buildings, with prefabricated concrete platform, metal railing and colorful metal plate covering outside the railings.

Figure 13. Examples of balconies on different facades
(a) Brick facade, (b) Concrete facade, (c) Metal facade, (d) Foam facade, (e) Wood facade, (f) Fiber cement facade, (g) Sone facade

10. Eaves (Figure 14)
Depending on the styles and materials of roofs and facades, there are many kinds of building eaves. In Gothenburg, most roofs of low and medium residential houses are slope, and flat for most high ones.

Figure 14. Various kinds of eaves in different houses of Gothenburg

11. Greenery facades
In Gothenburg, there are not many references of building façade greenery, and relatively simple. They can be divided into two kinds. One is adding metal or wood meshes on surfaces of the walls, and let plants, commonly hedera helix, climb up along the meshes (Figure 15); the other is hanging small pots outside windows or on rail-guards of balconies, and planting herbaceous plants in those pots (Figure 16).

Figure 15. Facade greenery in Gothenburg, plants climbing up along meshes

Figure 16. Facade greenery in Gothenburg, small planting pots outside window or on balcony

Suitable plants for vertical greenery in Gothenburg

For façade vertical greening of Gothenburg, choosing suitable plants of local climate and certain greening methods makes a key role on guaranteeing plants alive, achieving ideal effects and reducing maintenance costs. In this section, according to the climate of Gothenburg, which is in the 7 climate zone, and three interviews of local botanist, gardener and landscape architect, several kinds of plants for different vertical greening methods have been chosen. Most of these plants are evergreen, so they can still provide green views in the winter. In summer, some plants will have a variety of flowers, and make the greenery systems more beautiful.

All the images and information of plants' growing habits and features are from the following websites:
https://www.gardenia.net/plant,
https://www.odla.nu/inspiration,
https://www.greenleeandassociates.com,
http://www.missouribotanicalgarden.org/PlantFinder/PlantFinderDetails.aspx

1. Climbers

	Hedera Helix	Parthenocissus
		
Climate Zone	*5 - 11*	*4 - 8*
Growth	*perennials, evergreen*	*perennials, deciduous, semi-evergreen*
Flowering & Leaves	*dark-green leaves, greenish-white flowers*	*deep-green leaves in summer, orange, wine-red in fall, greenish-white flowers*
Size	*height 9-15m, wide 4-6m*	*height 9-15m, wide 3m*
Sunlight	*partial sun, shade*	*full sun, partial sun, shade*
Soil	*chalk, clay, loam, sand medium moist, well-drained*	*chalk, clay, loam, sand medium moist, well-drained*
Water	*medium*	*medium*
Tolerance	*drought, wind, full sun, a wide range of conditions*	*drought, wind, interventrion, full shade, a wide range of conditions*
Characteristic	*vigorous, fast-growing, no toxic, no smell, no allergic no damage to walls*	*easy to grow, vigorous, fast-growing, no toxic, no smell, no allergic, no damage to walls, but hard to remove, disease free,*
Maintenance	*hardy, low-maintenance*	*hardy, low-maintenance*
Greening type	*green facade direct/indirect, living wall planter*	*green facade direct*

Table 2. Planting information of Hedera Helix & Parthenocissus

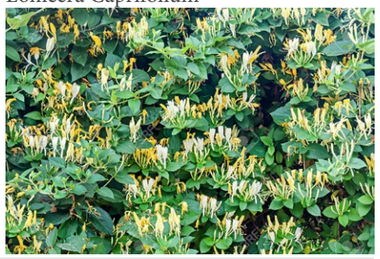
	Euonymus Fortunei	Lonicera Caprifolium
		
Climate Zone	*5 - 9*	*4 - 9*
Growth	*perennials, evergreen*	*perennials, deciduous*
Flowering & Leaves	*dark-green leaves with yellowrish, silver-white border or yellow spot, greenish flowers*	*dark-green leaves, brilliant flowers*
Size	*height 1.5-6m, wide 1.2m*	*height 4-6m, wide 2m*
Sunlight	*full sun, partial sun, shade*	*full sun, partial sun*
Soil	*chalk, clay, loam, sand medium moist, well-drained*	*clay, loam humus-rich, medium moist, well-drained*
Water	*medium*	*medium*
Tolerance	*drought, wind, full shade, a wide range of soils*	*full sun a wide range of conditions*
Characteristic	*easy to grow, vigorous no toxic, no smell, no allergic, no damage to walls*	*no toxic, no damage to walls, pest and disease free*
Maintenance	*hardy, low-maintenance*	*low-maintenance, minimal pruning*
Greening type	*green facade direct/indirect, living wall planter*	*green facade indirect, living wall planter*

Table 3. Planting information of Euonymus Fortunei & Lonicera Caprifolium

	Clematis	North-star Climbing Rose
		
Climate Zone	*7-10*	*1-7*
Growth	*perennials, evergreen*	*perennials, evergreen*
Flowering & Leaves	*deep-green leaves, abundance of white flowers*	*green leaves abundantly with small, white flowers*
Size	*height 6-12m*	*height 3-5m*
Sunlight	*full sun, partial sun*	*full sun, partial sun, shade*
Soil	*chalk, clay, loam, sand medium moist, well-drained*	*clay, loam, medium moist, well-drained*
Water	*medium*	*medium*
Tolerance	*exposure and climates*	*drought, wind, full shade,*
Characteristic	*easy to grow, vigorous, fast-growing, long flowering presence, rich diversity of flower shapes, not good companion plants*	*easy to grow, vigorous No toxic, scent smell no damage to walls*
Maintenance	*low-maintenance, no regular pruning*	*hardy, low-maintenance*
Greening type	*green facade indirect, living wall planter*	*green facade direct/indirect, living wall planter*

Table 4. Planting information of Clematis & North-star Climbing Rose

2. Hanging plants

	Hedera Helix	Vinca minor
		
Climate Zone	*5 - 11*	*4 - 9*
Growth	*perennials, evergreen*	*perennials, evergreen*
Flowering & Leaves	*dark-green leaves, greenish-white flowers*	*dark-green leaves, large violet-blue flowers*
Size	*hanging 1-1.5m*	*hanging 0.5-1.2m*
Sunlight	*partial sun, shade*	*full sun, partial sun*
Soil	*chalk, clay, loam, sand medium moist, well-drained*	*chalk, clay, loam, sand dry to medium moist, well-drained*
Water	*medium*	*low, medium*
Tolerance	*drought, wind, full sun, a wide range of conditions*	*drought, dry soil, rocky soil, full shade*
Characteristic	*vigorous, fast-growing, no toxic, no smell, no allergic no damage to walls*	*easy to grow, vigorous, fast-growing, no serious pest and disease issues, not aggressive*
Maintenance	*hardy, low-maintenance*	*hardy, low-maintenance, no regular pruning*
Greening type	*small pot, living wall planter, living wall modular*	*small pot, living wall planter, living wall modular*

Table 5. Planting information of Hedera Helix & Vinca minor

	Asplenium trichomanes	Lysimachia nummularia
		
Climate Zone	*5 - 8*	*3 - 8*
Growth	*perennials, evergreen*	*perennials, evergreen*
Flowering & Leaves	*bright green leaves*	*lime-green to chartreuse leaves, bright yellow flowers*
Size	*hanging 0.5-1m*	*hanging 0.6-1.2m*
Sunlight	*partial sun, shade*	*full sun, partial sun*
Soil	*chalk, clay, loam, sand moist, well-drained*	*chalk, clay, loam, sand moist, well-drained*
Water	*medium*	*medium*
Tolerance		*wind, full sun, poorly drainage rocky or wet soil*
Characteristic	*remains lush and fresh-looking throughout the year, disease and pest free*	*vigorous, fast-growing, disease and pest free*
Maintenance	*low-maintenance, dead or damaged fronds remove*	*hardy, low-maintenance*
Greening type	*small pot, living wall planter, living wall modular*	*small pot, living wall planter, living wall modular*

Table 6. Planting information of Asplenium trichomanes & Lysimachia nummularia

	Ipomoea tricolor
	
Climate Zone	*2-12*
Growth	*perennials, evergreen*
Flowering & Leaves	*deep-green leaves, blue flowers*
Size	*hanging 0.5-1m*
Sunlight	*full sun*
Soil	*chalk, loam, sand even-moist, well-drained*
Water	*medium*
Tolerance	
Characteristic	*vigorous, fast-growing, disease and pest free*
Maintenance	*low-maintenance, no pruning*
Greening type	*small pot, living wall planter, living wall modular*

Table 7. Planting information of Ipomoea tricolor

3. Potted herbaceous

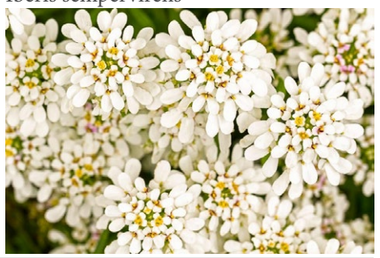
	Bergenia cordifolia	Iberis sempervirens
		
Climate Zone	*3 - 8*	*3 - 9*
Growth	*perennials, evergreen*	*perennials, evergreen*
Flowering & Leaves	*dark-green leaves in summer, big purplish-bronze leaves in winter, deep-pink flowers*	*dark-green leaves, white flowers*
Size	*height 0.3-0.6m*	*height 0.3m*
Sunlight	*full sun, partial sun*	*full sun, partial sun*
Soil	*chalk, clay, loam, sand moist, well-drained*	*chalk, loam, sand average moist, well-drained*
Water	*medium*	*low, medium*
Tolerance	*poor soils, heavy shade*	*drought, partial shade*
Characteristic	*vigorous, hardy undemanding, disease free, dislike hot and dry condition*	*vigorous, showy, no serious pest and disease issues,*
Maintenance	*hardy, low-maintenance, remove faded flower spikes*	*average-maintenance, especially in winter*
Greening type	*small pot, living wall hydroponic, living wall modular*	*small pot, living wall hydroponic, living wall modular*

Table 8. Planting information of Bergenia cordifolia & Iberis sempervirens

	Molinia caerulea	Achillea millefolium
		
Climate Zone	*5 - 9*	*3 - 9*
Growth	*perennials*	*perennials, evergreen*
Flowering & Leaves	*green to purplish bronze to golden leaves in different seasons*	*dark-green leaves orange to golden-bronze flowers*
Size	*height 0.2-0.3m*	*height 0.3-0.6m*
Sunlight	*partial sun, shade*	*full sun*
Soil	*clay, loam, sand medium moist, well-drained*	*chalk, loam, sand dry to medium moist, well-drained*
Water	*medium*	*low*
Tolerance	*drought, wet soils, partial shade*	*light shade, dry soils, heat, humidity pest and disease free, drought*
Characteristic	*vigorous, fast-growing, no toxic, no smell, no allergic disease and pest free*	*suitable for both warm and cool conditions, dried arrangement, showy, fragrant*
Maintenance	*low-maintenance, requires very little care*	*hardy, low-maintenance, easy to care*
Greening type	*small pot, living wall hydroponic, living wall modular*	*small pot, living wall hydroponic, living wall modular*

Table 9. Planting information of Molinia caerulea & Achillea millefolium

	Sesleria huefleriana	Antennaria dioica
		
Climate Zone	*4 - 11*	*3 - 9*
Growth	*perennials, evergreen*	*perennials, semi-evergreen*
Flowering & Leaves	*grey-green leaves, black-brown flowers*	*deep-green leaves, pink or white flowers*
Size	*height 0.5m*	*height 0.3-0.6m*
Sunlight	*half shade*	*full sun*
Soil	*chalk, loam, sand medium moist, well-drained*	*clay, loam, sand dry to medium moist, well-drained*
Water	*medium*	*low*
Tolerance	*in most of soils, coldness*	*drought, poor soils, dry and hot locations*
Characteristic	*vigorous, fast-growing no serious pest and disease issues*	*vigorous, fast-growing, no toxic, no smell, no allergic, disease and pest free*
Maintenance	*low-maintenance, light trimming in the fall*	*low-maintenance, tough and well-behave*
Greening type	*small pot, living wall hydroponic, living wall modular*	*small pot, living wall hydroponic, living wall modular*

Table 10. Planting information of Sesleria huefleriana & Antennaria dioica

	Nepeta x faassentii	Salvia nemorosa
		
Climate Zone	*3 - 8*	*4 - 11*
Growth	*perennials, evergreen*	*perennials, evergreen*
Flowering & Leaves	*deep-green leaves purplish flowers*	*deep-green leaves, dark purple flowers*
Size	*height 0.3-0.6m*	*height 0.25-0.3m*
Sunlight	*full sun, partial sun*	*full sun*
Soil	*chalk, loam, sand dry to medium moist, well-drained*	*chalk, loam, sand dry to medium moist, well-drained*
Water	*low*	*medium*
Tolerance	*dry soils, rocky soils, drought*	*half shade drought*
Characteristic	*easy to grow, vigorous, showy, fragrant, no serious pest and disease issues*	*easy to grow, vigorous, showy, fragrant, no serious pest and disease issues*
Maintenance	*low-maintenance*	*low-maintenance*
Greening type	*small pot, living wall hydroponic, living wall modular*	*small pot, living wall hydroponic, living wall modular*

Table 11. Planting information of Nepeta x faassentii & Salvia nemorosa

	Dianthus Deltoides
	
Climate Zone	*3 - 10*
Growth	*perennials, evergreen*
Flowering & Leaves	*deep-green leaves, pink flowers*
Size	*height 0.15-0.3m*
Sunlight	*full sun*
Soil	*chalk, loam, sand dry to medium moist, well-drained*
Water	*low*
Tolerance	*drought, light shade*
Characteristic	*easy to grow, vigorous, showy, fragrant, no serious pest and disease issues,*
Maintenance	*hardy, low-maintenance*
Greening type	*small pot, living wall hydroponic, living wall modular*

Table 12. Planting information of Dianthus Deltoides

Common types of facade greening

In this section, there are five diagrams and some references to show five common types of vertical greening on building facades, and the relative information of them.

1. Green facade-direct. (Figure 21)

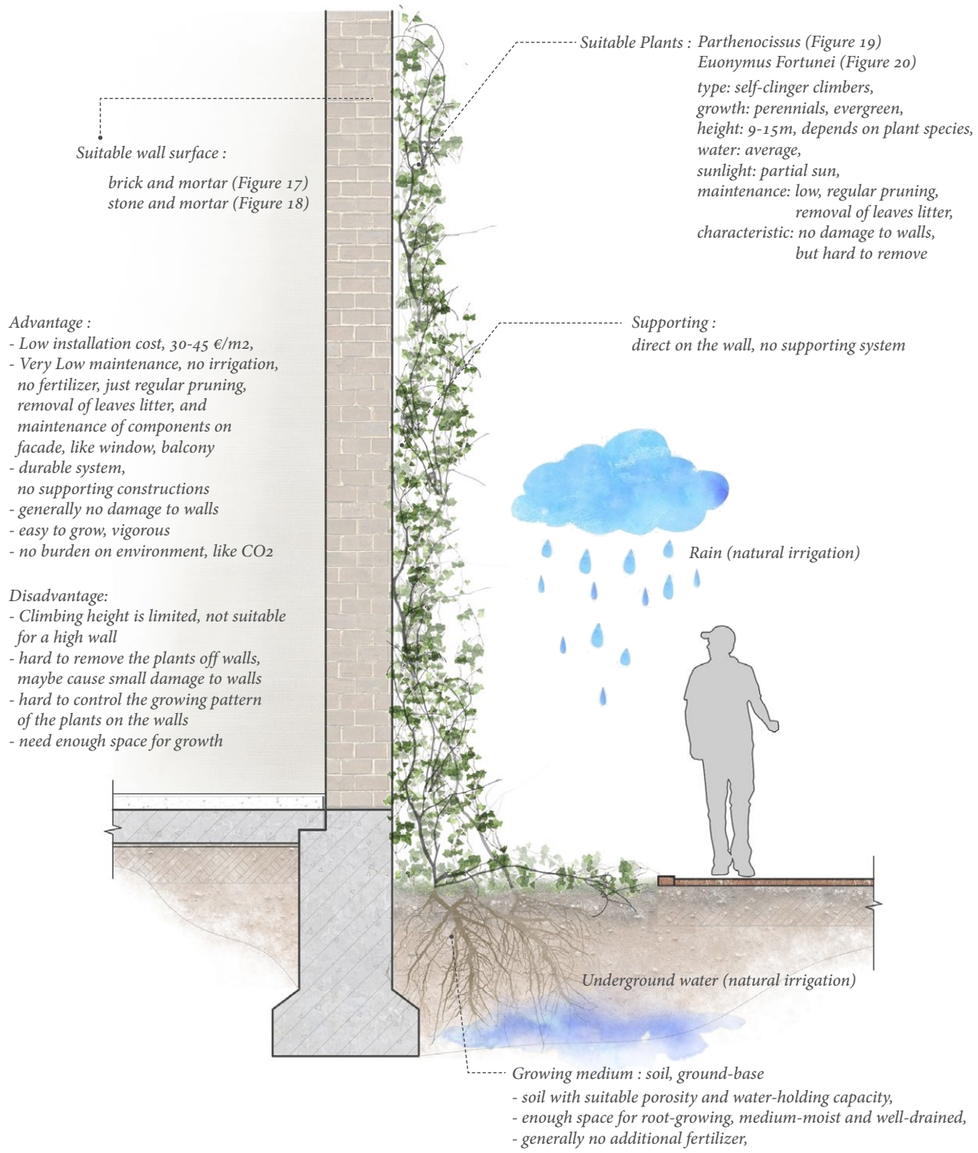


Illustration 1. General information & factors of green facade-direct

Figure 17. Brick and mortar facade

Figure 18. Stone and mortar facade

Figure 21. A building with green facade - direct

Figure 19. Parthenocissus

Figure 20. Euonymus Fortunei

Figure 22. Hedera Helix

Figure 23. Clematis

Figure 27. A building with green facade - indirect

Figure 24. Steel cable supporting

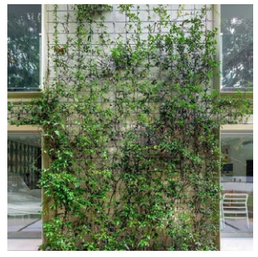


Figure 25 Steel mesh supporting

Figure 26. Wood mesh supporting

2. Green facade-indirect. (Figure 27)

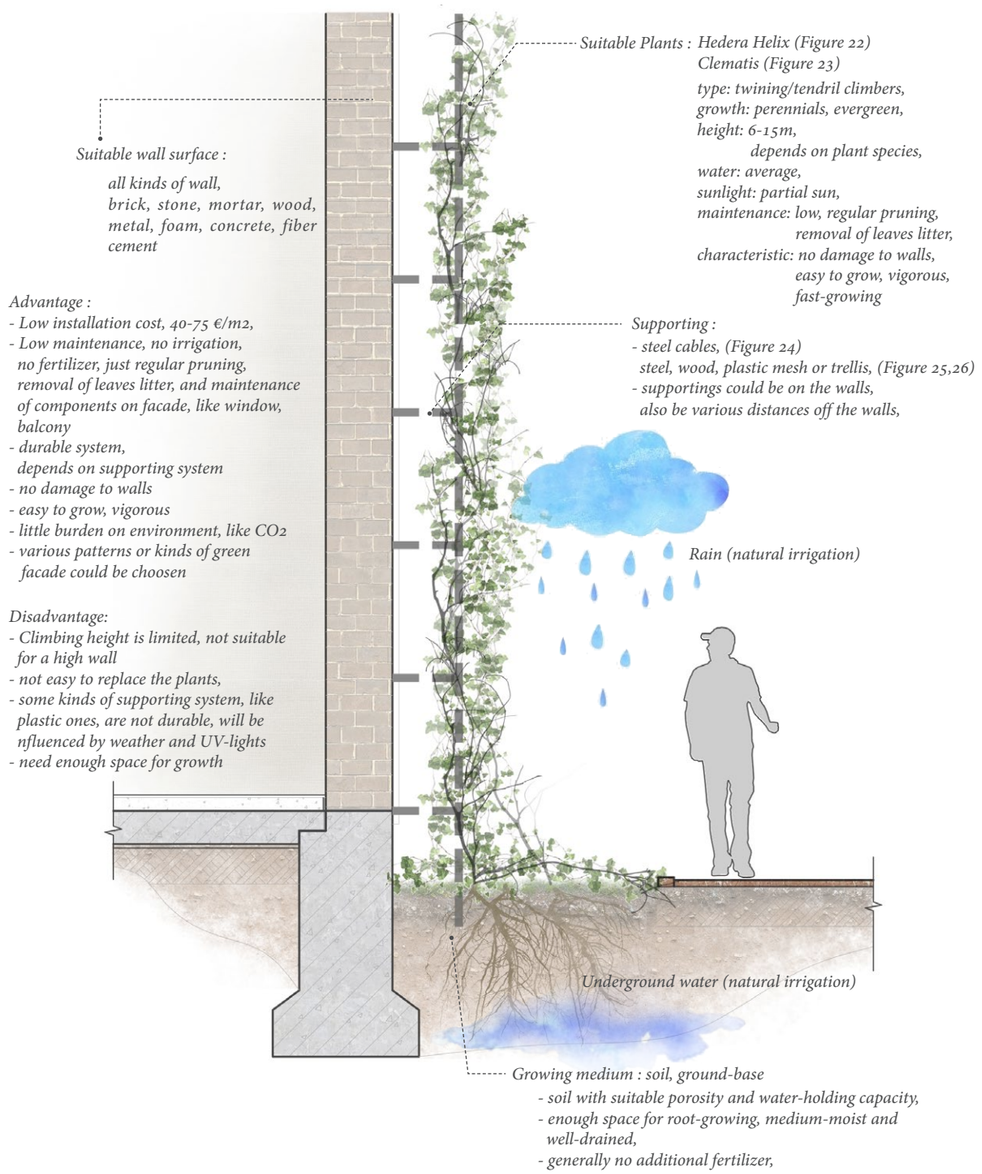


Illustration 2. General information & factors of green facade-indirect

3. Living wall-planter. (Figure 32)

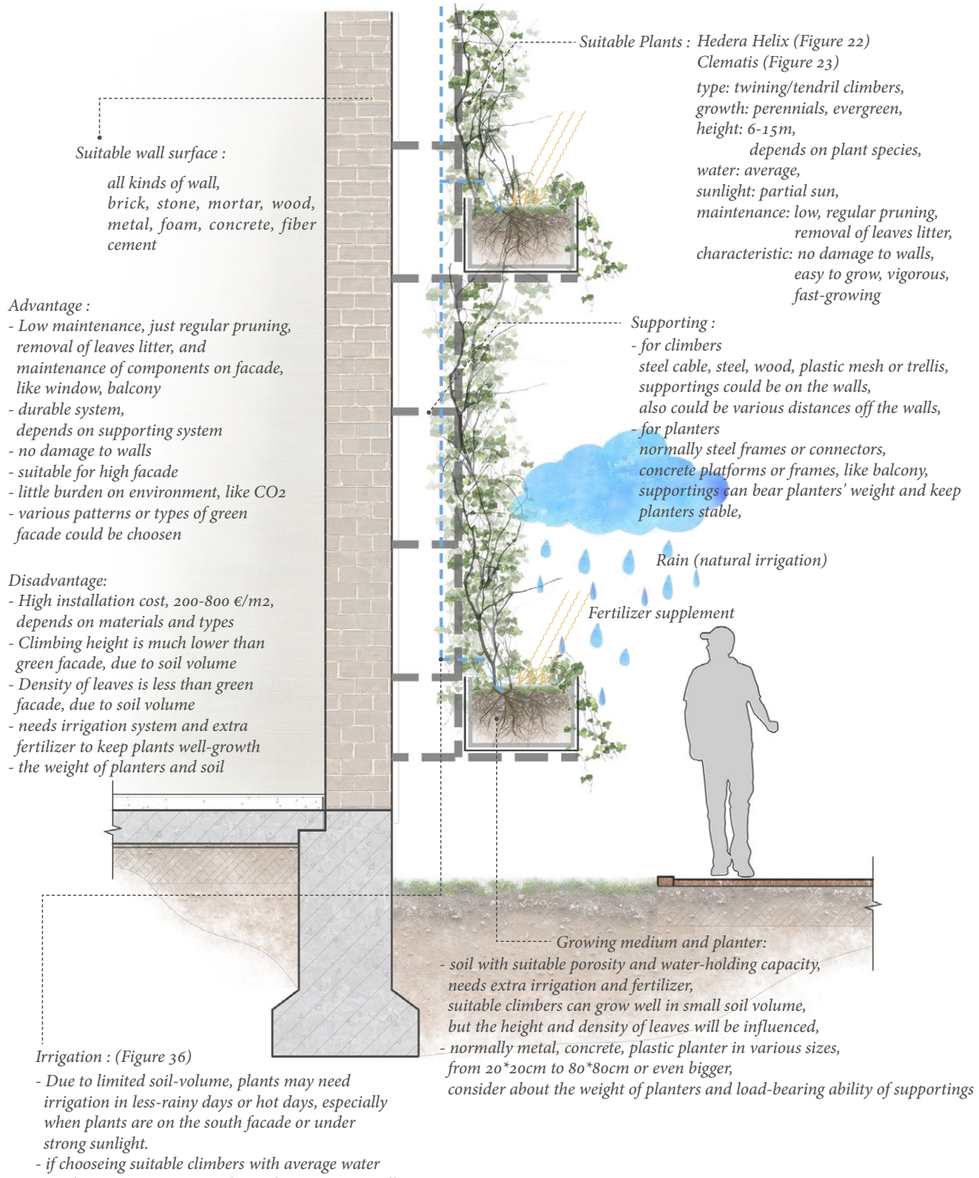


Illustration 3. General information & factors of living wall-planter

4. Living wall-hanging plants. (Figure 35)

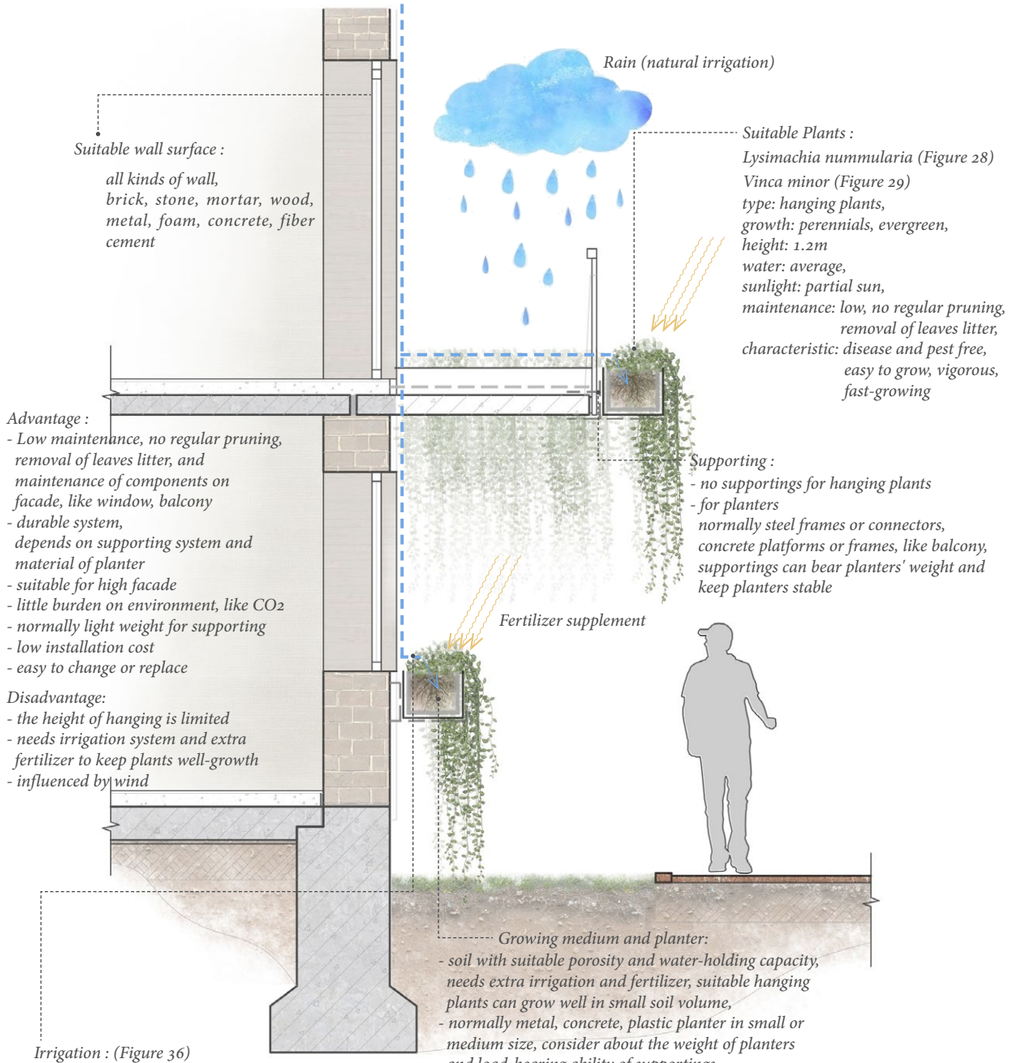


Illustration 4. General information & factors of living wall-hanging plants

Figure 28. Lysimachia nummularia

Figure 29. Vinca minor

Figure 30. Bergenia cordifolia

Figure 31. Iberis sempervirens

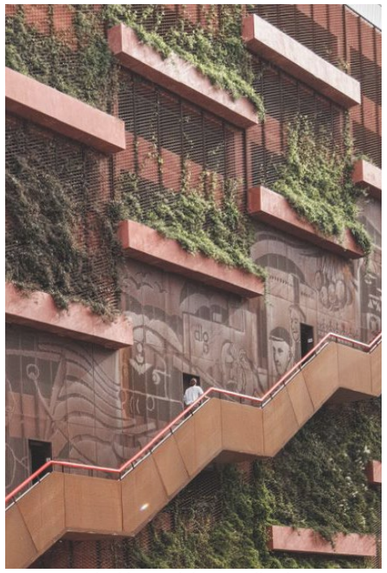


Figure 32. A building with living wall - planter

Figure 33. Sesleria huefleriana

Figure 34. Salvia nemorosa

Figure 35. A building with living wall - hanging plants

Figure 37. A building with small planting pots

Figure 36. Drip irrigation pipe

5. Small planting pots. (Figure 37)

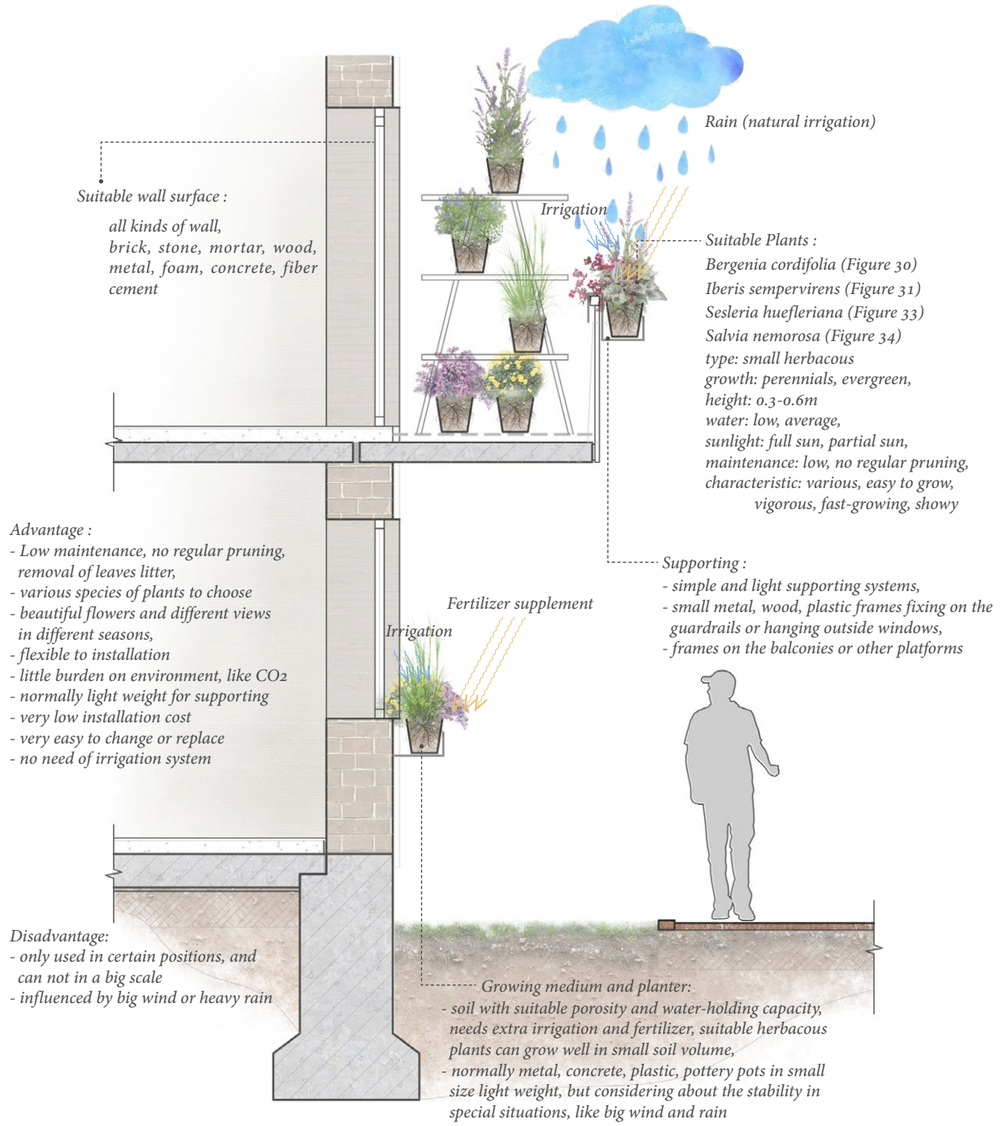


Illustration 5. General information & factors of small planting pots

STRATEGIES

Seeking suitable plans for different conditions of buildings and available resources

Plans for different building conditions

There are many different kinds of residential buildings in Gothenburg, and each building also has its own situation. They may be different in orientations, heights, materials, components, locations, surroundings or maintenance, and all these differences may have different impacts when making facade greening regenerations. There are also some buildings which are not suitable of facade greening, such as those with historical or memorial value, or those with a high density of windows on facades. In this section, providing some suitable greenery solutions for the right conditions.

1. Facade orientation and plants

Facade orientation	*South*	*East*	*West*	*North*
Climate	*sunhours a year 1950 hours* *main wind direction 30% of a year*	*sunhours a year 1204 hours* *main wind direction 21% of a year*	*sunhours a year 1154 hours* *main wind direction 34% of a year*	*sunhours a year 408 hours* *main wind direction 15% of a year*
Suitable plants	*- like full sun or partial sun, but shade-tolerant* *- wind-tolerant* *- drought-tolerant, or more irrigation in summer*	*- like partial sun, but shade-tolerant* *- more irrigation in summer*	*- like partial sun, but shade-tolerant* *- wind-tolerant* *- more irrigation in summer*	*- like shade or partial shade, but light-tolerant*
Typical plants	*climber: Euonymus Fortunei*  *hanging: Lysimachia nummularia*  *herbaceous: Iberis sempervirens*  *Achillea millefolium* 	*climber: Lonicera Caprifolium*  *hanging: Vinca minor*  *herbaceous: Nepeta x faassentii*  *Bergenia cordifolia* 	*climber: North-star Climbing Rose*  *hanging: Vinca minor*  *herbaceous: Nepeta x faassentii*  *Bergenia cordifolia* 	*climber: Hedera Helix*  *hanging: Asplenium trichomanes*  *herbaceous: Molinia caerulea*  *Sesleria huefleriana* 

Table 13. Sunhours and wind situation of different orientations and suitable plants for different orientations

2. Facade materials

Facade material	*brick or stone with mortar*	*others (foam, metal, wood, concrete, fiber cement, etc.)*
suitable methods	*green facade-direct,* *green facade-indirect,* *living wall-planter*	*green facade-indirect,* *living wall-planter*
suitable climbers	*green facade-direct: self-clinger climber like, Parthenocissus, Euonymus Fortunei* *green facade-indirect: twining/tendril climber like, Hedera Helix, Clematis* *living wall-planter: twining/tendril climber like, Hedera Helix, Clematis*	*green facade-indirect: twining/tendril climber like, Hedera Helix, Clematis* *living wall-planter: twining/tendril climber like, Hedera Helix, Clematis*

Table 14. Suitable greening methods and plants for different facade materials

3. Facade height

All the climbers have the limitation of growth height, so they can not climb to cover a high wall from the ground. It is important to understand their limitations when choosing greening methods and plants for different facade designs.

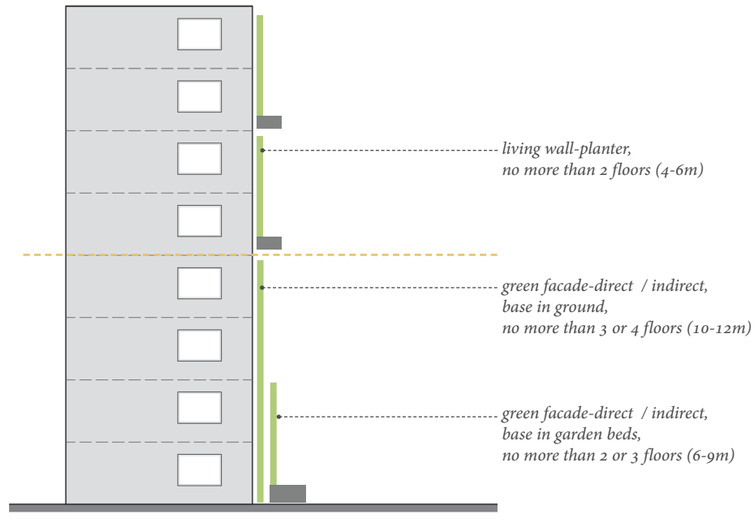


Illustration 6. Suitable greenery height for different facad levels

4. Facade components

Window and balcony are the main components of residential facades, different kinds of components and different combinations of components make various facades. The differences need certain suitable solutions.

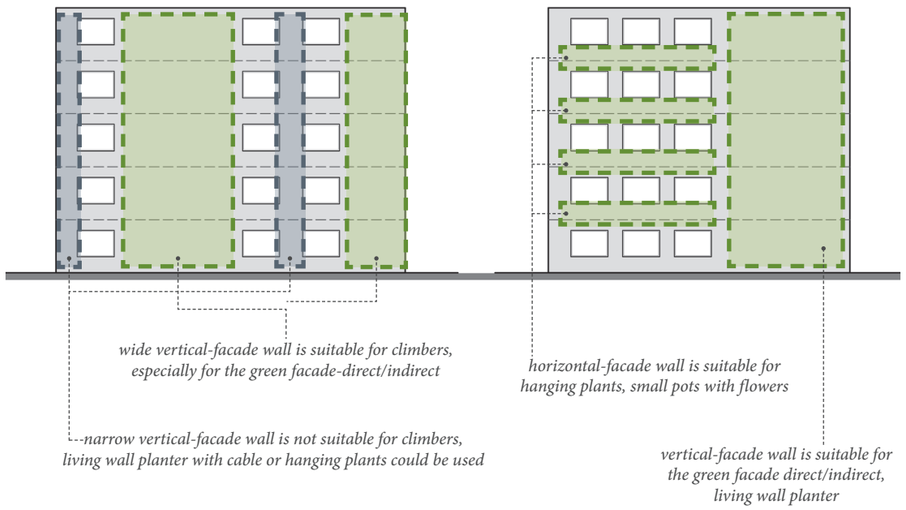


Illustration 7. Suitable greenery types and plants for different wall situations

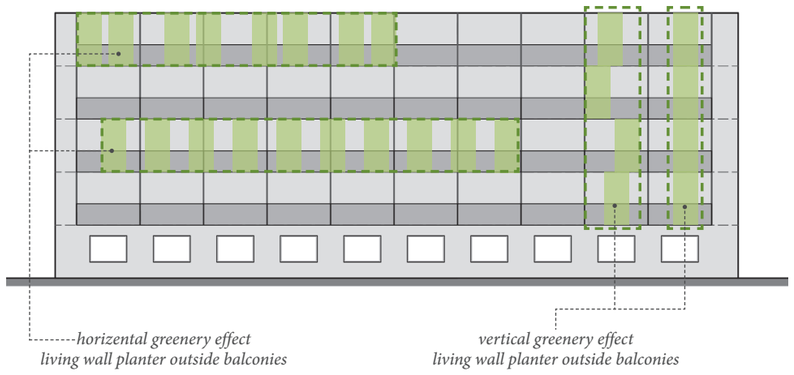


Illustration 8. Different greenery patterns of living wall planter on balconies

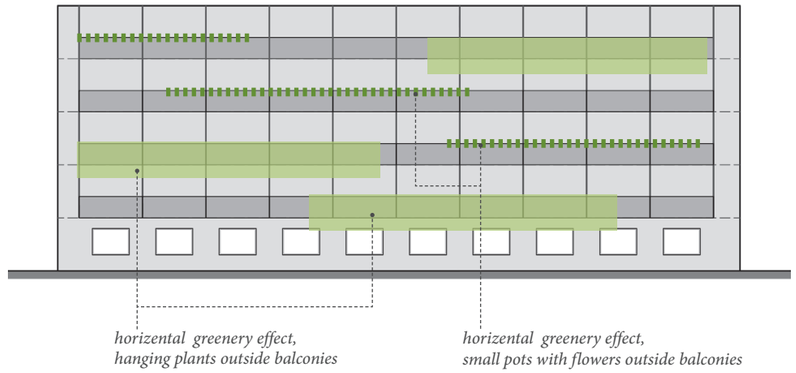


Illustration 9. Hanging plants and flowers on balconies

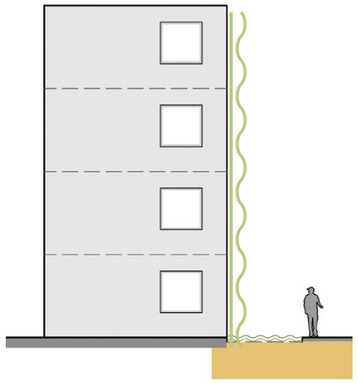
5. Facade durability and maintenance

Due to different durability of facade materials, some kinds of facades need maintenance or regenenration by a period of time, like metal facades, foam facades, wood facades, but some facades can last for many decades without maintenance or regeneration, such as brick facades and stone facades. Sometimes, facade greening, especially the climbers, will have negative influence on the maintenance or repairments of building facades, so choosing suitable greening needs to be considered before the design.

Facade material	*Need of maintenance*	*Suitable plant & greening method*	*Possible implications*
brick stone	*little maintenance or regeneration*	*self-clinger climbers green facade-direct*	*Removing self-clinger climbers from the wall may cause damage to the construction, so facade with little maintenance is suitable.*
metal foam wood concrete fiber cement	*more frequent maintenance or regeneration*	*twining/tendril climbers green facade-indirect, & living wall-planter*	*Removing twining/tendril climbers on climbing-aids is much easier than self-clinger climbers, so they are more suitable for facades needing regular maintenance or regeneration.*

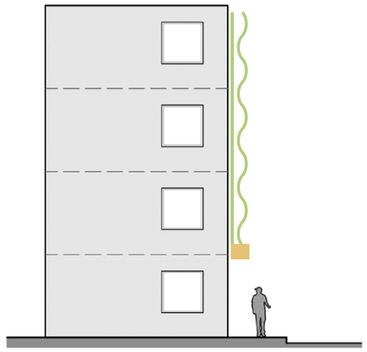
Table 14. Need of maintenance, suitable greenery types and plants for different facades

6. Surrounding conditions



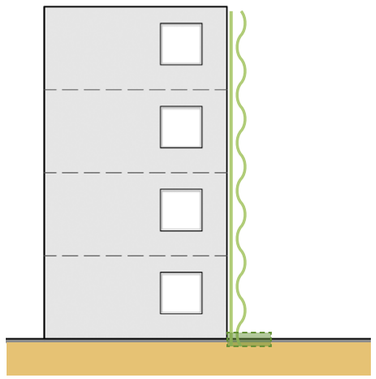
1. There are natural spaces between the building and the road.

Climbers, by the way of green facade-direct/indirect, could be used and planted directly in the natural ground.



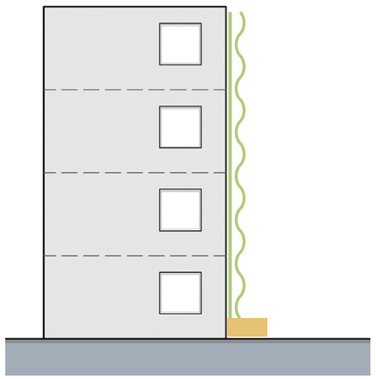
2. The road is just next to the building.

The greenery is better to start from the second floor, by living wall-planter, hanging plants, or small pots.



3. The road is away from the building, but the ground is covered by hard surface, like cement.

If the basement is soil, part of the hard surface next to the building could be removed, and planting climbers in the soil.



4. The road is away from the building, but the ground is covered by hard surface, like cement.

If the basement is a parking space or others, there is no soil for planting. Garden beds on the ground could be used for climbers.

Illustration 10. Suitable greenery solutions for different building surroundings

Utilization of recycle materials

There are a large amount of waste materials from various fields, and reusing them in new projects can help to reduce costs and CO_2 emission. This thesis, I do studies on using suitable recycled materials in my façade greening design, in order to achieve the low-cost aim.

In terms of the supporting system of the façade greenery, it mainly consists of three parts, the load-bearing part, the planter and the climbing-aid part (Figure 38, Figure 39). The load-bearing part is fixed on the wall or other building components, and its function is to afford the weight of the whole system; the planter is used to cultivate vegetation in a high level, and it take the load of soil and water; the climbing-aid part is to help climbers grow, generally with kinds of cable, nets or trellis, and it needs to take the weight of the plants.Not all the façade greenery systems have all the three parts; the green façade direct normally has none; the green façade indirect does not have planters; the living wall hanging plant and small potted flowers only have planter and loading-bearing part.

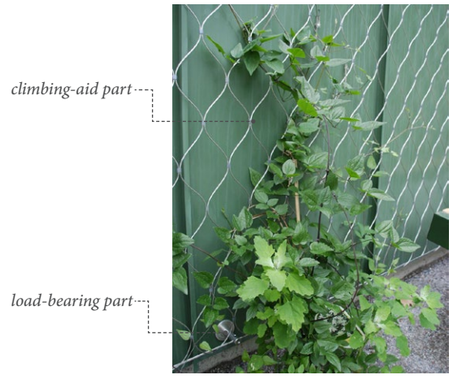


Figure 38. Facade greenery supporting system with nets

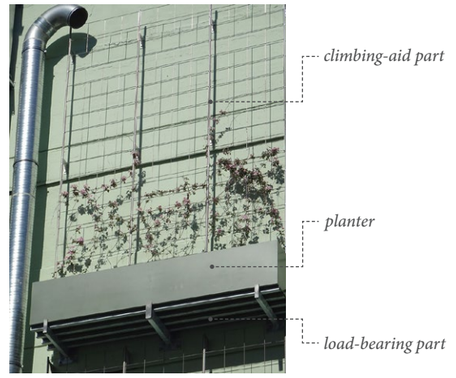


Figure 39. A living wall planter with metal grids

According to the features and functions of these three parts, choosing suitable recycled materials for them:

1. Load-bearing part

Recycled steel is an ideal material for the load-bearing part. There are a large amount of waste steel from construction industry, which could be recycled for new use. These recycled steels are also in a variety of styles and sizes for different needs in new projects, for example, L-shape steel, H-shape steel, U-shape steel, T-shape steel, steel bars, rectangle or round steel pipe, ans so on (Figure 40). They are strong and durable enough for the load-bearing part, and they are also easy to being connected with other components and being fixed on the building. These recycled steel can also be prefabricated in factory into required shape and size.

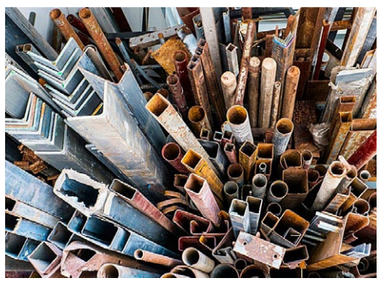


Figure 40. Different kinds of recycled steel

2. Planter

Recycled steel plate could be used to make new planters. The steel plate is strong and durable enough to afford the weight of soil and water. It can be processed into various sizes and combined into desired shapes by welding or mechanical connection. (Figure 41)

Figure 41. Recycled steel plates

3. Climbing-aid part

In terms of the climbing-aids, it is better to choose those strong, durable, water-proofing and light materials to resist the power of plant-growth, rain and snow, wind and to reduce the whole weight. The recycled ship ropes (Figure 42), normally made of hemp, and the recycled climbing ropes made of nylon (Figure 43) are both good choices for cable climbing-aids. The recycled hemp nets (Figure 44) and the recycled fishing nets (Figure 45) made of nylon are both good choices for nets climbing-aids.

Figure 42. Ship ropes made of hemp

Figure 43. Climbing ropes in different colors

Figure 44. Recycled hemp nets

Figure 45. Fishing nets

Irrigation system and rain recycle

Suitable irrigation system is crucial to the success and sustainability of façade greenery. This thesis focuses on three topics of the irrigation system: how to save water, how to save power and how to give water to plants in right time and right amount.

In large greening or landscape projects, automatic irrigation systems are usually a good choice as they can be controlled easily and save labor costs. Generally, the automatic system consists of the following parts: water source, controller(and sensors), pump, filter, pipes and irrigation kits (Illustration 11).

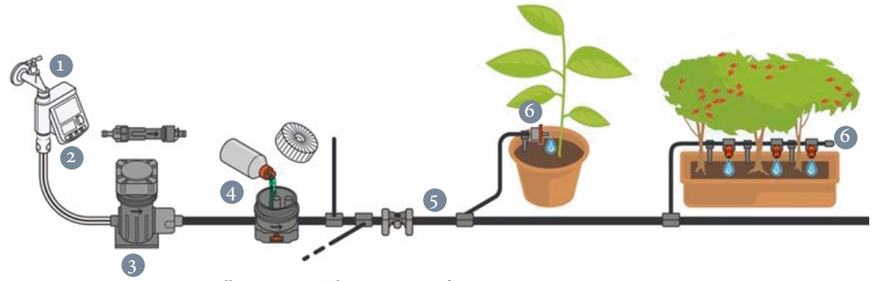


Illustration 11. The main parts of an automatic irrigation system

1. *Water source. (water could be from tape, tank, well, and so on.)*
2. *Controller. (controling the system when to irrigate and how much to irrigate; in some smart system, there are sensors working with controllers together; there are also different kinds of controllers, mechanical, electronics, smart) (Figure 46)*

(a) (b) (c)

Figure 46. Three kinds of controller for irrigation system (a) mechanical (b) electronics (c) smart

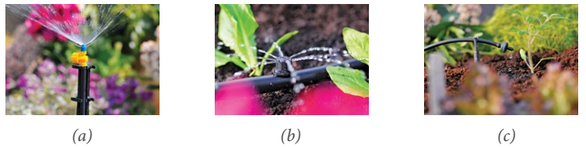
3. *Pump. (give power to the water to reach high or far positions; not necessary, depending on the water source and the size of the system; need power to work) (Figure 47)*

Figure 47. pump for irrigation system

4. *Filter. (filter out impurities in water; normally used when the water source is from recycled water, rivers or ponds)*
5. *Pipes, connectors and fix. (Figure 48)*

Figure 48. pipes, connectors and fix for irrigation system

6. *Irrigation kits. (Figure 49)*



(a) (b) (c)

Figure 49. Different kinds of irrigation kits (a) micro jets (b) sprinkler (c) drip

The following items are some strategies which could help develop sustainable irrigation system and help to save water, save power, and be suitable for plant-growth:

1. Saving water
--Collecting rain water on the roof and using this recycled rain water for irrigation could help to save water; Using drip as the irrigation kit is also a good way to avoid water waste; Using sensors and controller equipment to find the right time and amount for irrigation, which can also make full use of water.

2. Saving power
--Normally, the pump need a lot of power to send the water to plants. A system which only use the gravity of water instead of the pump could help to save much power.

3. Suitable irrigation in right time and amount
--Using sensors to mornitor the weather temperature, the soil moisture, and if it rains or not, and giving feedback to the controller. This could help system to find the right time and amount of irrigation.

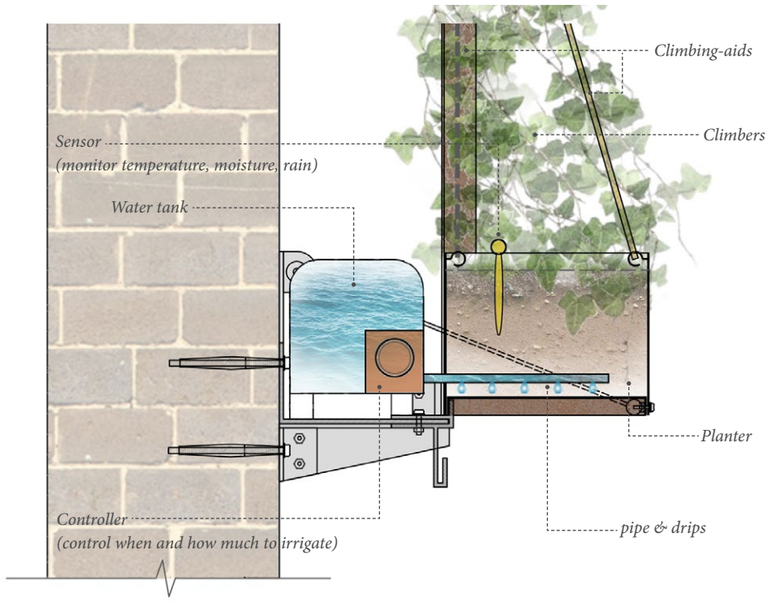


Illustration 12. Section of water tank and planter.
(The water tank for storing rain water is hidden behind the living wall planter.)

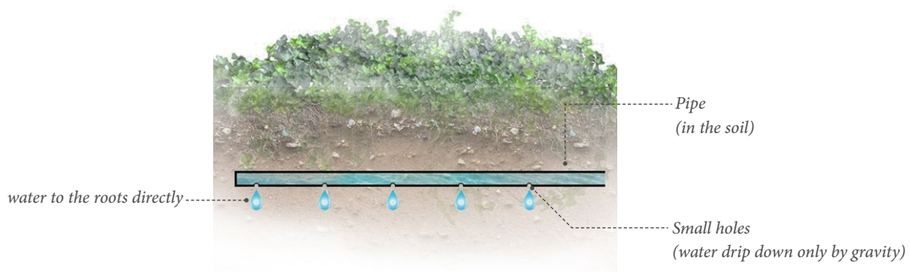


Illustration 13. Pipe and dirp irrigation.
(The pipe with small holes goes into the bottom of the soil to water the roots directly by dripping way)

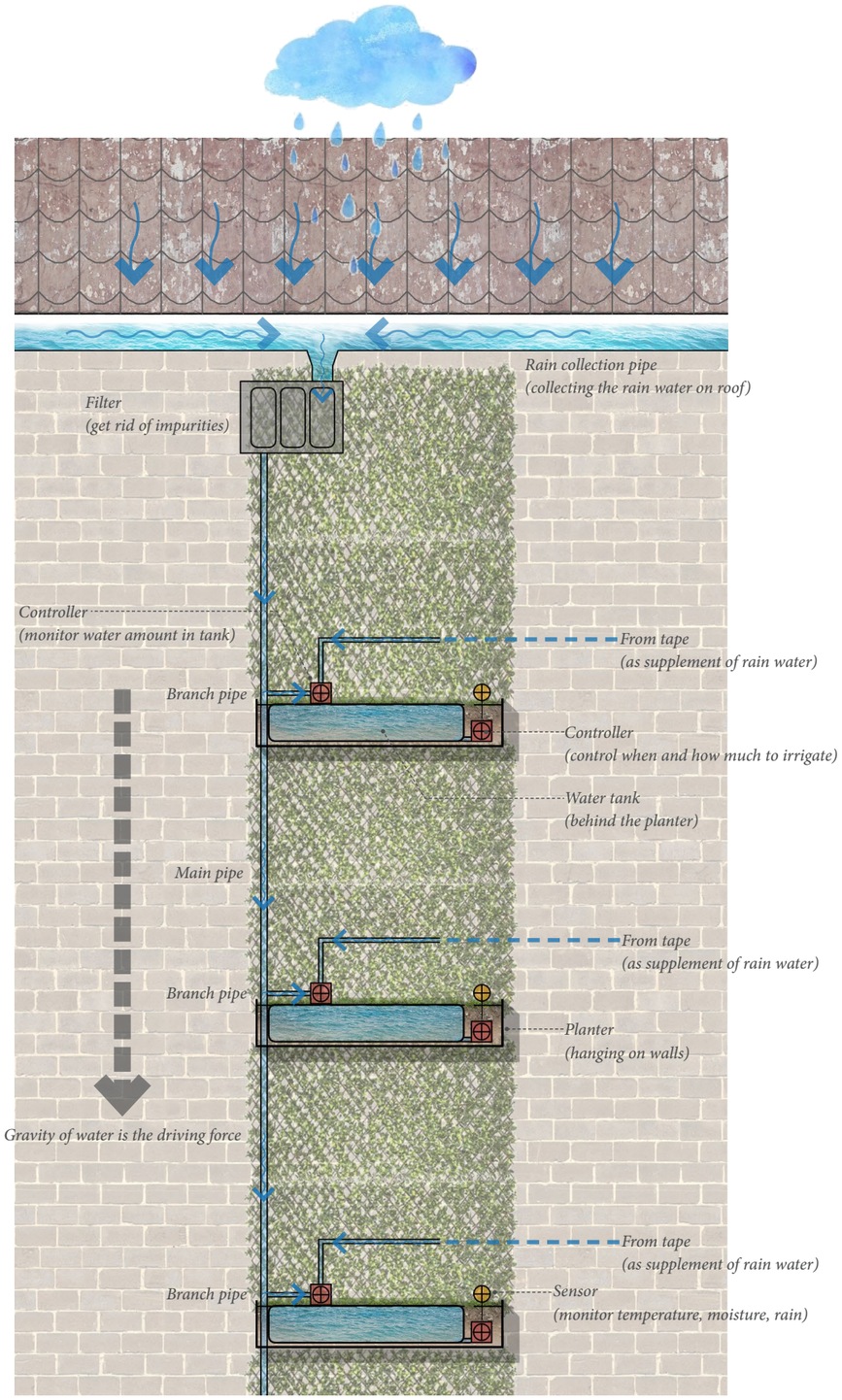


Illustration 14. Irrigation system with recycled rain water and automatic controller.
(This is the concept of a sustainable irrigation system for living wall planter. The system will collect rain water on the roof, and send the water to the storing tanks behind planters only by the gravity. By the feedback from sensors in the soil, the controllers will decide when and how much to irrigate. All the system is behind the greenery.)

Living wall planter module

Living wall planter is a common and effective way of façade greening, which can achieve to planting vegetation on a high level. Generally, planters and climbing-aids are fixed on the façade firstly, and then climbers are planted in the box after putting the soil in (Figure 50). However, there are some common issues for this method:

-- It usually takes three or even several years for most the perennial climbers to grow up and meet ideal landscape effects.

-- Due to less maintenance or unsuitable daylight, in some situation, plants will grow slowly or have poor growth.

-- It is hard to replace the plants when there are growth problems, like pests or illness, and the growth of new ones will also take a long time.

-- The size and weight of living wall planters are normally large, so their structures are in big sizes, which is not elegant enough.

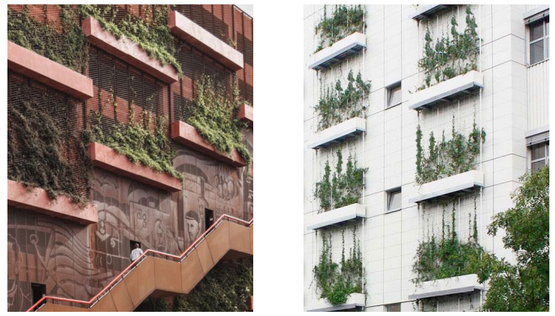


Figure 50. Conventional living wall planter with climbers on building facades

To solve the above issues, this thesis tries to find a new kind of living wall planter system in a module way. The new module will be in smaller sizes than the conventional ones, in order to reduce the weight and the structure size. This small and light module could be easily installed on the loading-bearing frame which has been already fixed on building facades, and taken down to replace another module. Climbers will be planted in modules and grow well before the modules are installed on buildings. The module which has plant-growth problem will be taken down and go back to the garden for therapy. A new module with good plants will be installed on at the same time.

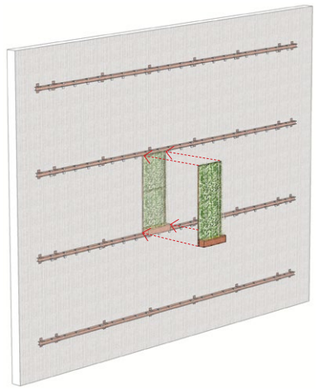
Conventional living wall planter	*Living wall planter module*
planters and climbing-aids (big size) manufacturing in factory	*living wall planter module (small size) manufacturing in factory*
installing on building facades	*sending to garden & planting climbers in the module to full growth*
putting soil in planters & cultivating climbers	*installing modules on building facades by workers*
after 3 or several years plants will grow up to ideal effect	*achieving ideal effect immediately*
when poor growth or illness removing bad plants	*when poor growth or illness removing the module and sending back to garden*
planting new climbers	*installing new module with good plants*
after 3 or several years plants will grow up to ideal effect	*achieving ideal effect immediately*
	process

Table 15. The difference between the processes of conventional living wall planter & new living wall planter module

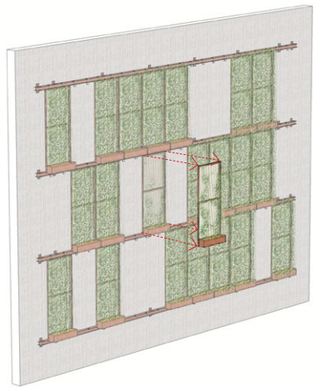
Step 1. living wall planter module made in the factory

Step 2. send modules to garden to cultivate plants

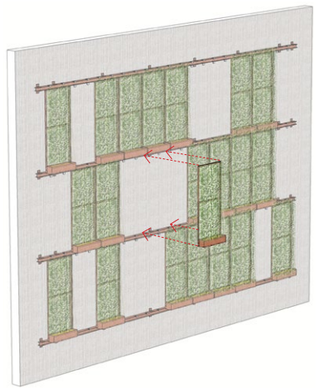
Step 3. installing load-bearing fixings on building facades



Step 4. fixing modules on the beams



Step 5. when the module is in poor growth, taking down it and sending back to the garden



Step 6. fixing new module with good growth on the beams

Illustration 15. The process of adding living wall planter module system on building facades

DESIGN

Integrate greening design for typical residential facades in Gothenburg

Choosing facades for design

The first step of design work is to choose design objects, the residential building facades in Gothenburg. These selected facades should be representative, which means they should have different kinds of typical features in age, orientation, height, material, components, and surroundings.

Generally, there are four principles of choosing the ogjects :
1. The object lies in the downtown area, which has high building density and is lack of greenlands. It needs more greenery to make up the loss of natural land.
2. The object has a unspectacular facade apperance without historical or memorial value. Facade greenery can be a kind of upgrading to make this kind of building more beautiful.
3. The object is medium-height building, around 3 to 10 floors. The medium-height building is the majority of the residential buildings in Gothenburg.
4. Adding greenery on the facade of the object can provide avaiable landscape views to the public and the community.

The following three residential facades for design:

1. Brick facade. (Figure 51)

This building is a student dormitory with a red brick facade, and was built around the 1950s. A lot of students lives here, and they would like to do all kinds of activities in the square next to the building. Its facade is relatively old and boring. Therefore, greening the facade can make it more beatuiful and interesting, and also bring the students on the square new landscape. Moreover, the 2 to 3 floor high brick facade is very suitable for self-clinger climbers to grow with very little maintenance, which means it will be easy to get greenery effects with low costs.

Figure 51. The first chosen facade for design with brick material

Type:	*student dormitory*	*Material:*	*brick*
Age:	*built in 1950s*	*Components:*	*small windows and doors, no balconies*
Orientation:	*east*	*Surroundings:*	*square with hard ground*
Height:	*2-3 floors*	*Maintenance:*	*little*

Table 16. Information of the brick-facade building

2. Foam facade. (Figure 52)

This building is a medium-height residential building, and lies in an area with many similar houses. Its facade is relatively old and unspectacular. The distance between the building and others is not far, which means when residents watch out of their windows, most the views are nearby houses. Therefore, adding greenery on its facade could make it elegant and provide people in the next buildings a new kind of landscape view.

Figure 52. The second chosen facade for design with foam material

Type:	*residence*	*Material:*	*foam*
Age:	*facade regeneration in 1990s*	*Components:*	*separated windows and vertical balconies*
Orientation:	*south*	*Surroundings:*	*natural ground and away from road*
Height:	*6-7 floors*	*Maintenance:*	*regular maintenance for the foam layer*

Table 17. Information of the foam-facade building

3. Concrete facade. (Figure 53)

This building is a medium-height residential building, and lies in a region with many similar houses. It is also a city centre place with high density of buildings and limited green spaces. This large and industrial style building with concrete facades give people an unvibrant feeling. Therefore, adding greenery on its facade could make this cold and soild building more kind to dwellers. Moreover, greening the facade full of balconies will bring the plants into people's daily life, and create interesting interactions.

Figure 53. The third chosen facade for design with concrete material

Type:	*residence*	*Material:*	*concrete and metal*
Age:	*built in 1970s*	*Components:*	*all balconies*
Orientation:	*west*	*Surroundings:*	*natural ground and away from road*
Height:	*9 floors*	*Maintenance:*	*yes*

Table 18. Information of the concrete-facade building

Design of the brick facade building

The brick facade material of this building is suitable for self-clinger climbers to grow up without any supporting stuff, and the height of two to three floors is also easy for the plants to climb up to the top. Therefore, choosing green facade direct and planting the climbers in ground soil is a ideal way for its facade greening, and in this way the greenery system will need little maintenance and few construction stuffs, which means it will be in low cost of both constructing and mainenance. However, the narrow vertical wall between windows is not advantageous for green facade direct, so another way, green facade indirect with cables will be used instead.

Illustration 16. Greening solutions for different facade conditions

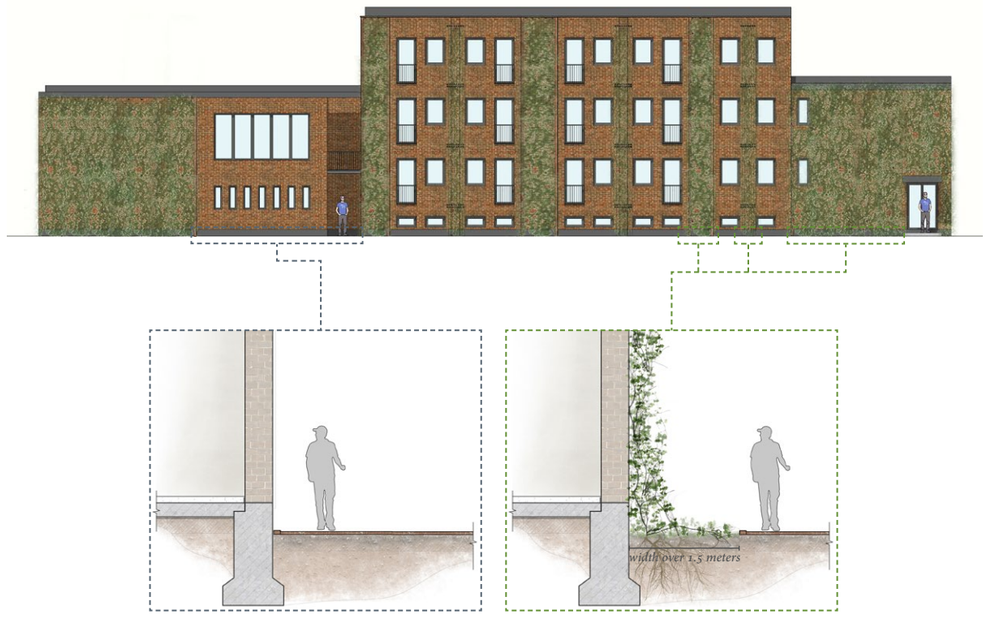
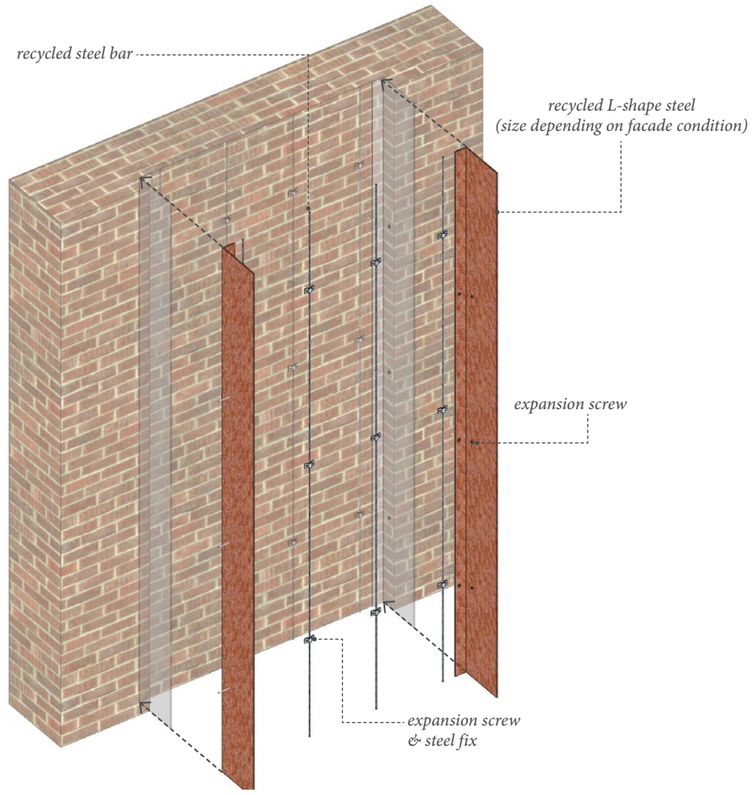


Illustration 17. Facade greening effect & the solution for surrounding condition

1. Green facade direct

For the wide vertical-walls, green facade direct with self-clinger climbers are the first choice. Although self-clinger climbers do not need any aid to climb up on a brick wall, there are two common issues for the plants to achieve ideal effects. The first is that the climbers will grow in different directions instead of only climbing up straightly; the other is that it is hard to control the climbing-range of plants on the facade without any aid. Therefore, in the design, some simple climbing-aids are installed to help the climbers have a right growth-direction and not to climb randomly. Recycled steels are used as the aids to reduce the cost.



In this system, the recycled L-shape steels are used to set the growth-range of the climbers on facades, and the steel bars will act the role to help plants climb in right direction.

Illustration 18. Climbing-aids of green facade direct

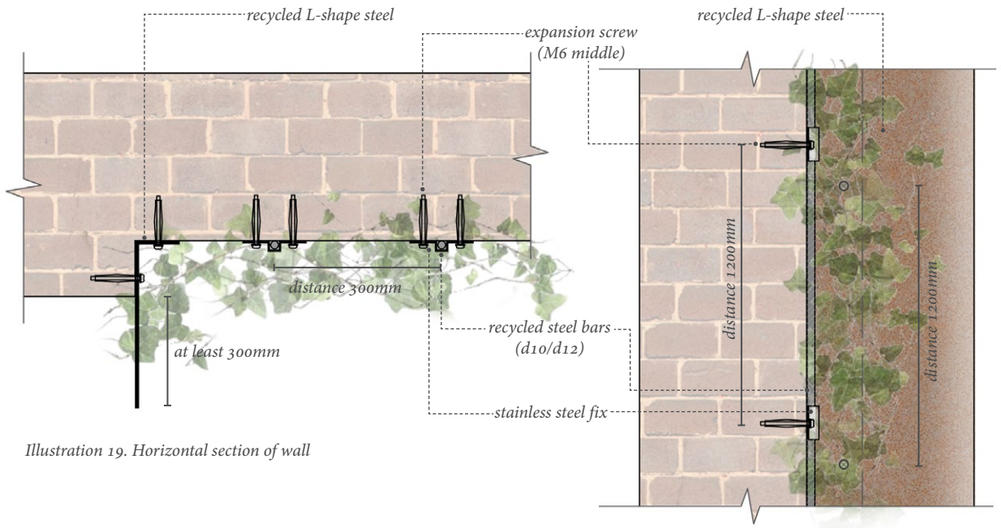
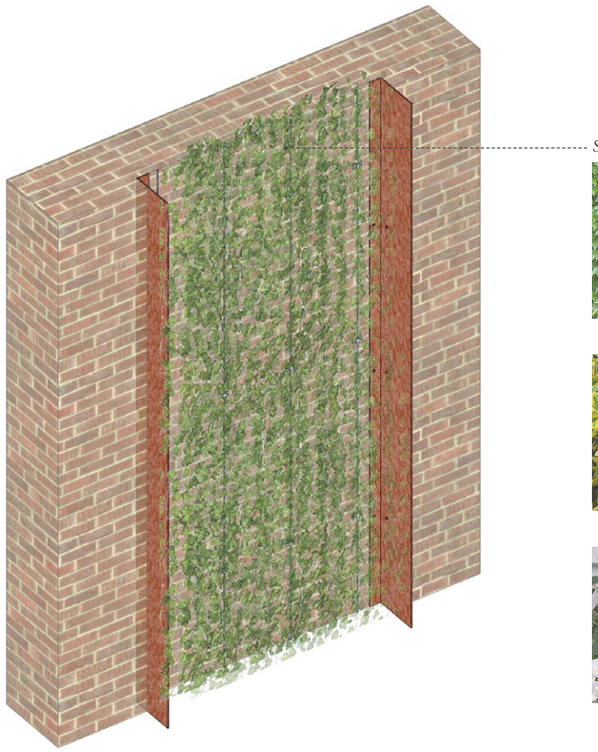


Illustration 19. Horizontal section of wall

Illustration 20. Vertical section of wall



Parthenocissus

Euonymus fortunei

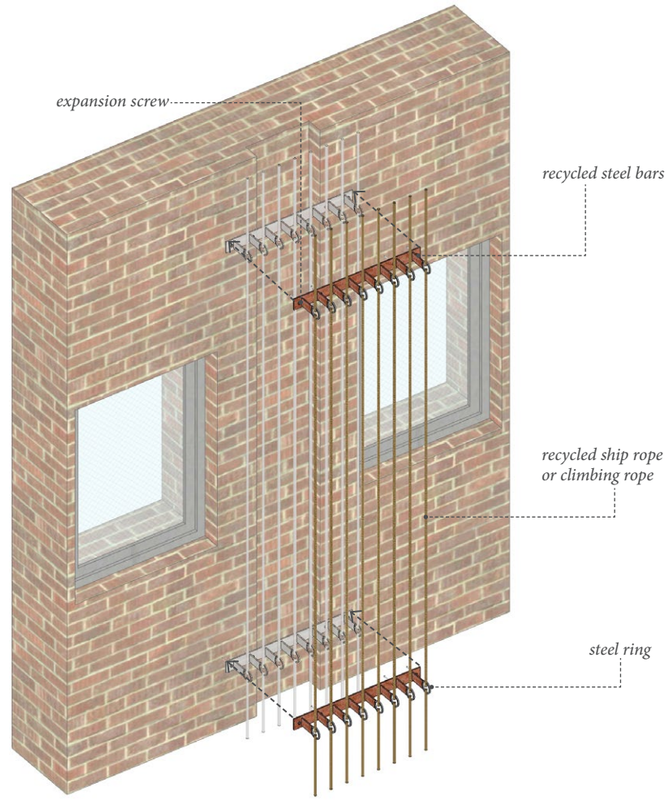
Climbing rose

In this project, self-clinger climbers can grow well on the brick facade. Parthenocissus, Euonymus fortunei and Climbing rose are suitable plants of this eastern facade, because they grow well in full sun or partial sun condition, and they are also wind tolerance.

Illustration 21. Green facade direct system on brick wall

2. Green facade indirect - cable

For the narrow vertical-walls, like the part between too near windows of this building, it is hard for the self-clinger plants to climb up in such condition. The green facade indirect with cables or ropes as the climbing-aids can solve this problem. Recycled ship rope or climbing rope could be used as substitute of the conventional stainless cable. At last, euonymus fortunei and climbing rose are ideal plants for it, because they climb up no matter if there are climbing-aids.



In this system, the recycled steel bars and steel rings are welded together and connected by ropes between each floor. Plants climb up along these ropes, and there is a distance between the ropes and the wall surface. The distance between ropes could be around 100mm to 200mm, depending on the plants.

Illustration 22. Climbing-aids of green facade indirect with cable

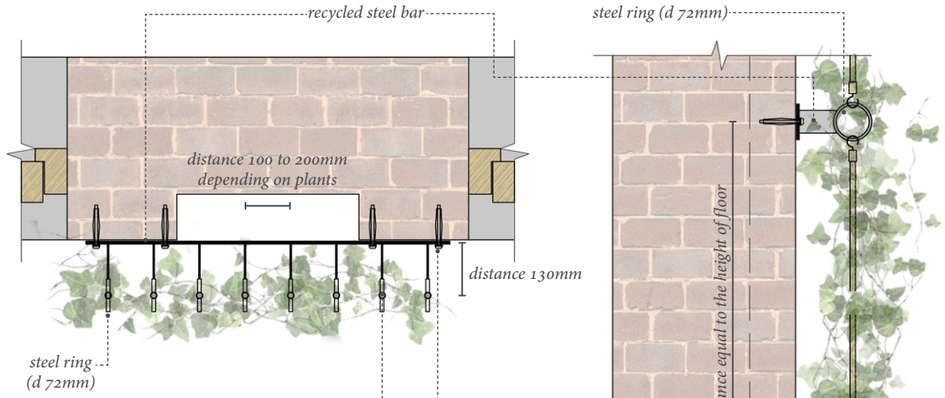
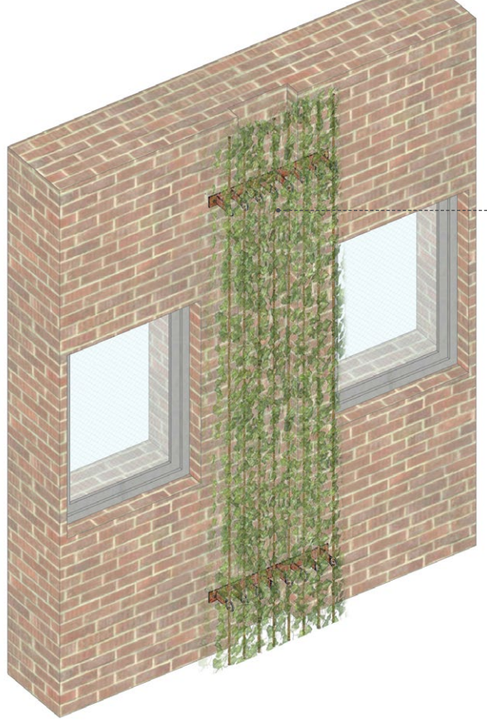


Illustration 23. Horizontal section of wall

Illustration 24. Vertical section of wall



Euonymus fortunei

Climbing rose

In the green facade indirect system, twining or tendril climbers can grow well by the help of ropes. Euonymus fortunei and Climbing rose are suitable plants of this facade, because they can both climb along ropes and on the wall directly.

Illustration 25. Green facade indirect system with cables on brick wall

Design of the foam facade building

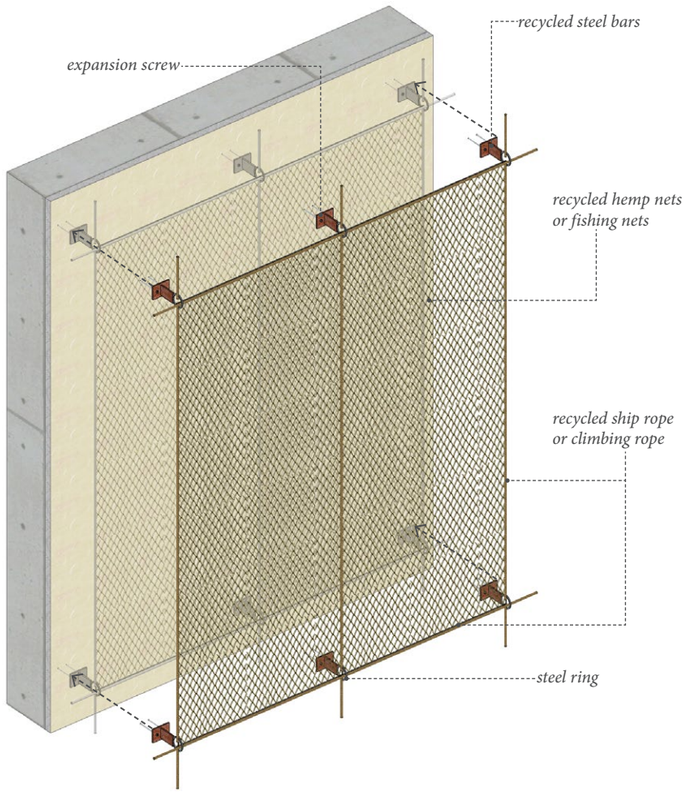
Climbing plants can not go up directly on the foam material, so climbing-aids are needed for vertial greenery. In terms of the wide vertical-walls, green facade indirect is good choice for the low part under three floors, and living wall planter module will be used for the hight part. As for the balconies, living wall planter module can also be used in the similar way with the ones on walls, which can generate a kind of vertical greenery between two balconies. At last, it is hard to have climbers on the horizental walls between two floors, so small living wall planters with hanging plants or flowers is a good choice. It can make a green or colorful belt under windows.

Illustration 26. Greening solutions for different facade conditions

Illustration 27. Facade greening effect of the foam building

1. Green facade indirect

Climbers can not go up along the foam facade directly, so climbing-aids are necessary for the plants to reach the high level. In the design, recycled steel bars with rings are the supporting and connecting one, and recycled ropes link the rings together by both vertical and horizental directions. Recycled nets are fixed by the ropes as the climbing-aid for plants.



In this system, the recycled steel bars and steel rings are welded together and connected by ropes in both vertical and horizental directions. Nets are fixed on the ropes. Plants climb up along these nets, and there is a distance between the nets and the wall surface. Ropes are connected with the rings by hook on the head of ropes, and nets are tied on the ropes. Therefore, it will be easy to take off the ropes and nets, when there is maintenance of the wall.

Illustration 28. Climbing-aids of green facade indirect

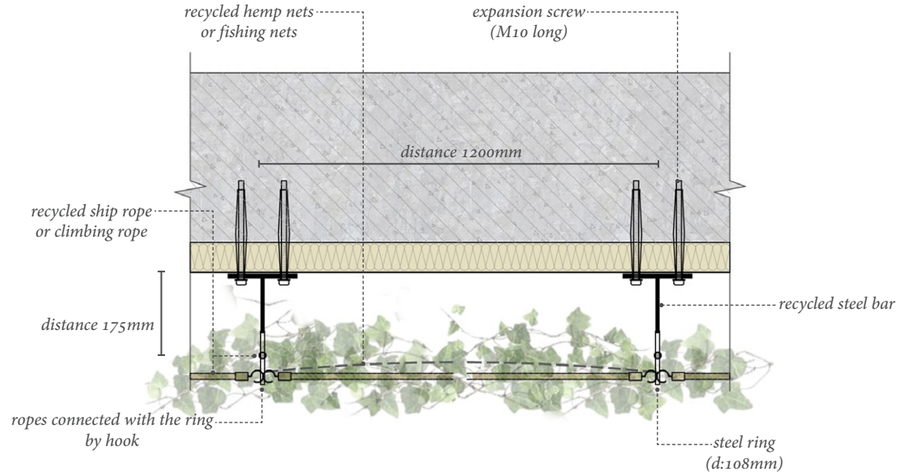


Illustration 29. Horizontal section of wall

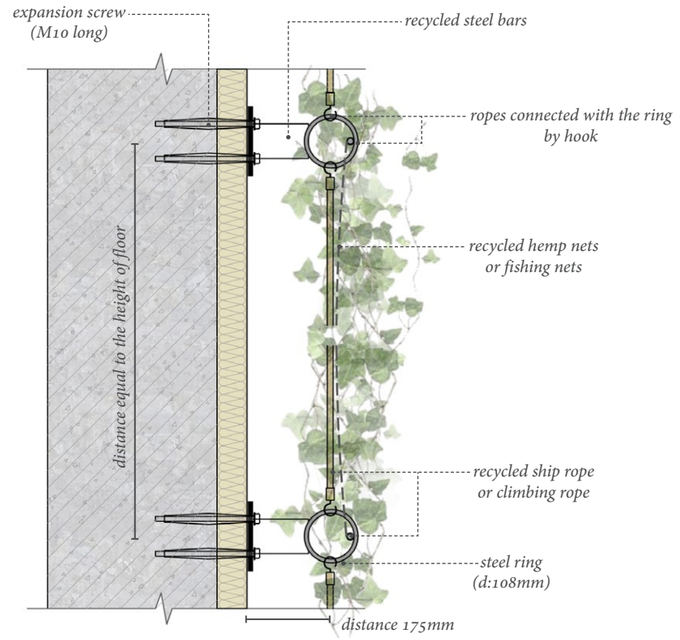


Illustration 30. Vertical section of wall

In the green facade indirect system, twining or tendril climbers can grow well by the help of ropes and nets. Lonicera Caprifolium and Clematis are suitable plants of this southern facade, because they grow well in full sun or partial sun condition. Hedera Helix is usually better to live under partial sun or shading place, so it is not a good choice for this facade.

Illustration 31. Green facade indirect system on foam wall

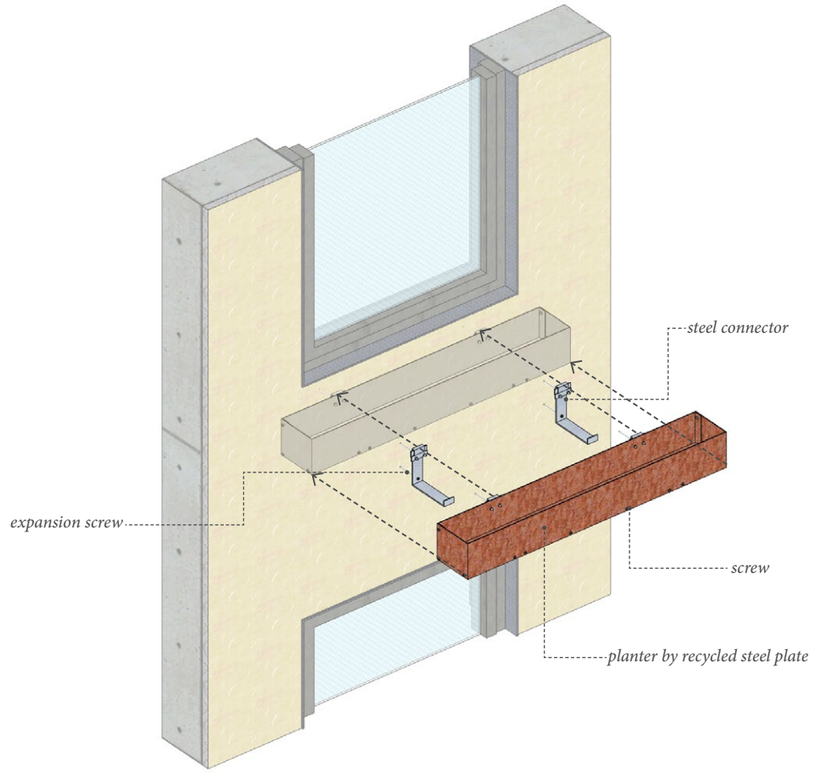
Suitable plants:

Lonicera caprifolium

Clematis

2. Living wall planter with hanging plants or flowers

Living wall planter with hanging plants and flowers are suitable for narrow horizental walls between the windows of two next floors, and generate a kind or greenery belt. The hanging plants and herbaceous flowers normally do not need much soil, so the planters could be in small size and light. When the planters are put outside the window, the dwellers could put their own plants in as they like, and these plants could also be maintained by their owners instead of by workers or automatic systems. Of course, these small plants usually only need little maintenance. In the design, planters are made of recycled steel plates, and fixed on the wall by simple connectors.



In this system, the planter is made of three pieces of recycled steel plates, and the pieces are got together by screw. Two L-shape steel connectors are fixed on the wall by expansion screws, and they are the supports for the planter.

Illustration 32. Planter for hanging plants or flowers

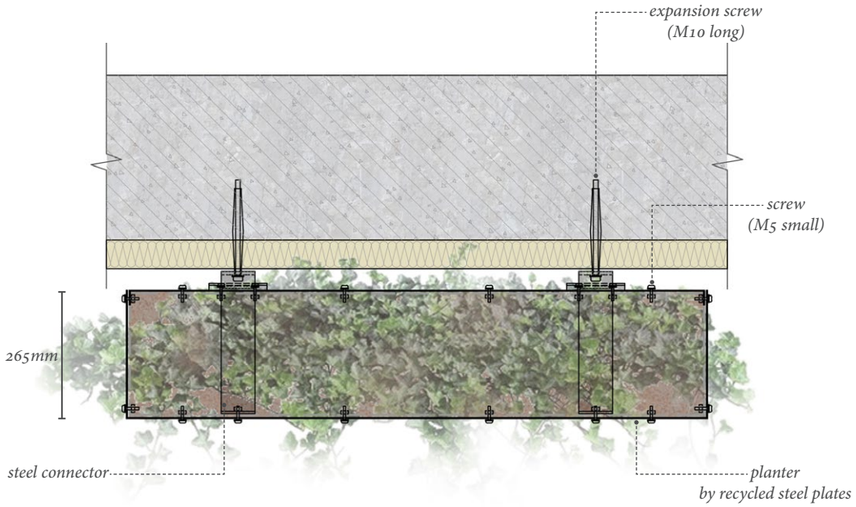


Illustration 33. Horizontal section of wall

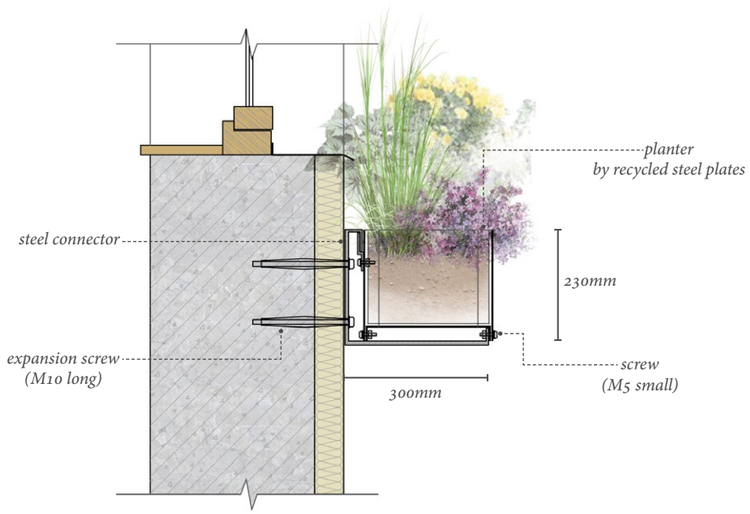
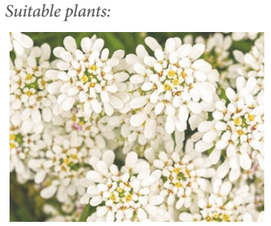


Illustration 34. Vertical section of wall

Beacause the facade is to the south, the plants should be full-sunlight tolerance and like to grow under full-sunlight or partial-sunlight condition. Moreover, wind tolerance is also important for the plants, because, during over 30% days of a year, wind is from the south. The suitable flowers are Iberis semperbirens, Salvia nemorosa, and Dianthus deltoides.

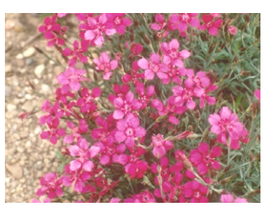
Illustration 35. Living wall planter with flowers

Suitable plants:



Iberis semperbirens

Salvia nemorosa



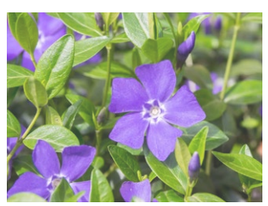
Dianthus deltoides

Beacause the facade is to the south, the plants should be full-sunlight tolerance and like to grow under full-sunlight or partial-sunlight condition. Moreover, wind tolerance is also important for the plants, because, during over 30% days of a year, wind is from the south. The suitable hanging plants are Lysimachia nummularia, Vinca minor and Ipomoea tricolor.

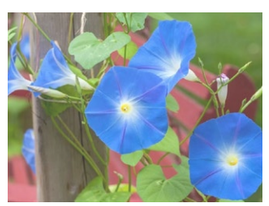
Illustration 36. Living wall planter with hanging plants

Suitable plants:

Lysimachia nummularia



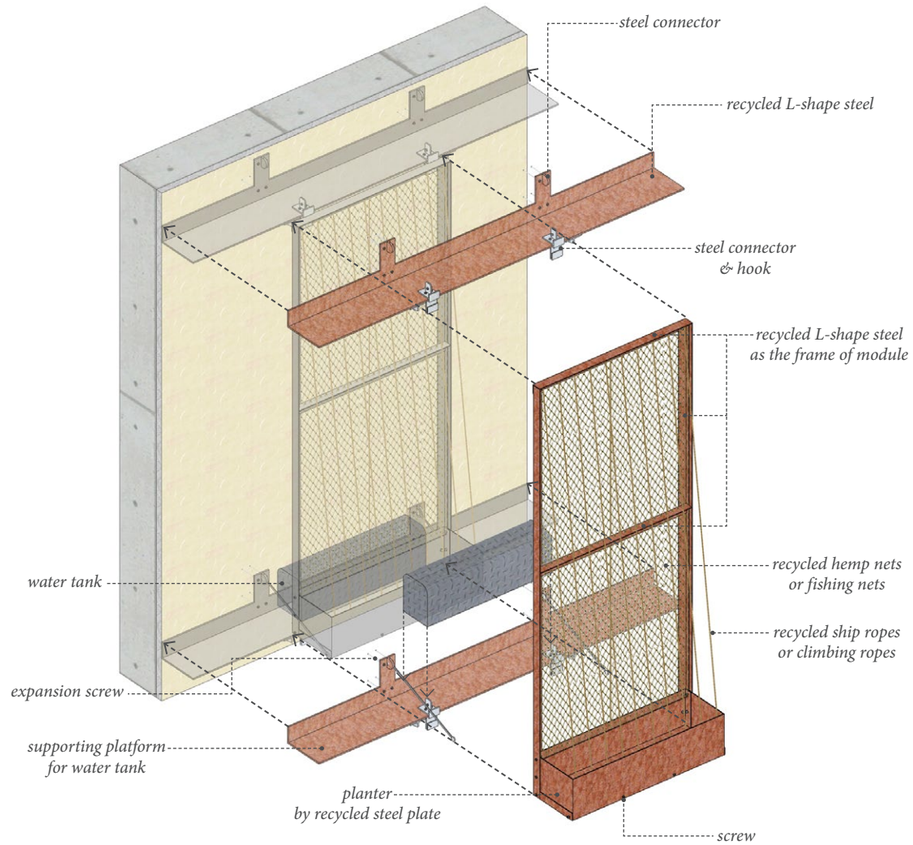
Vinca minor



Ipomoea tricolor

3. Living wall planter module

Living wall planter module is more flexible than the conventional living wall planter with climbers. It has smaller size and weight, with 1.2-meter width and one-floor height. The module consists of a planter, climbing-aids and supporting frames. Because the plants do not need to climb up highly, the module does not need much soil and water, which means a relatively small planter in light weight is enough. The module is made of various kinds of recycled materials, like recycled steel plates for the planter, recycled L-shape steel for the frame, recycled ropes and nets for the climbing-aids.



In this system, horizontal beams made of recycled L-shape steel are fixed on the wall firstly, and then, the module will be hanged on the beams by four steel connecters and hooks. In this way, the arrangement of modules on a wall could be flexible and in various patterns. When the wall needs maintenance or some modules need to be replaced, they can be easily taken down and re-installed.

Illustration 37. Construction of living wall planter module on wall

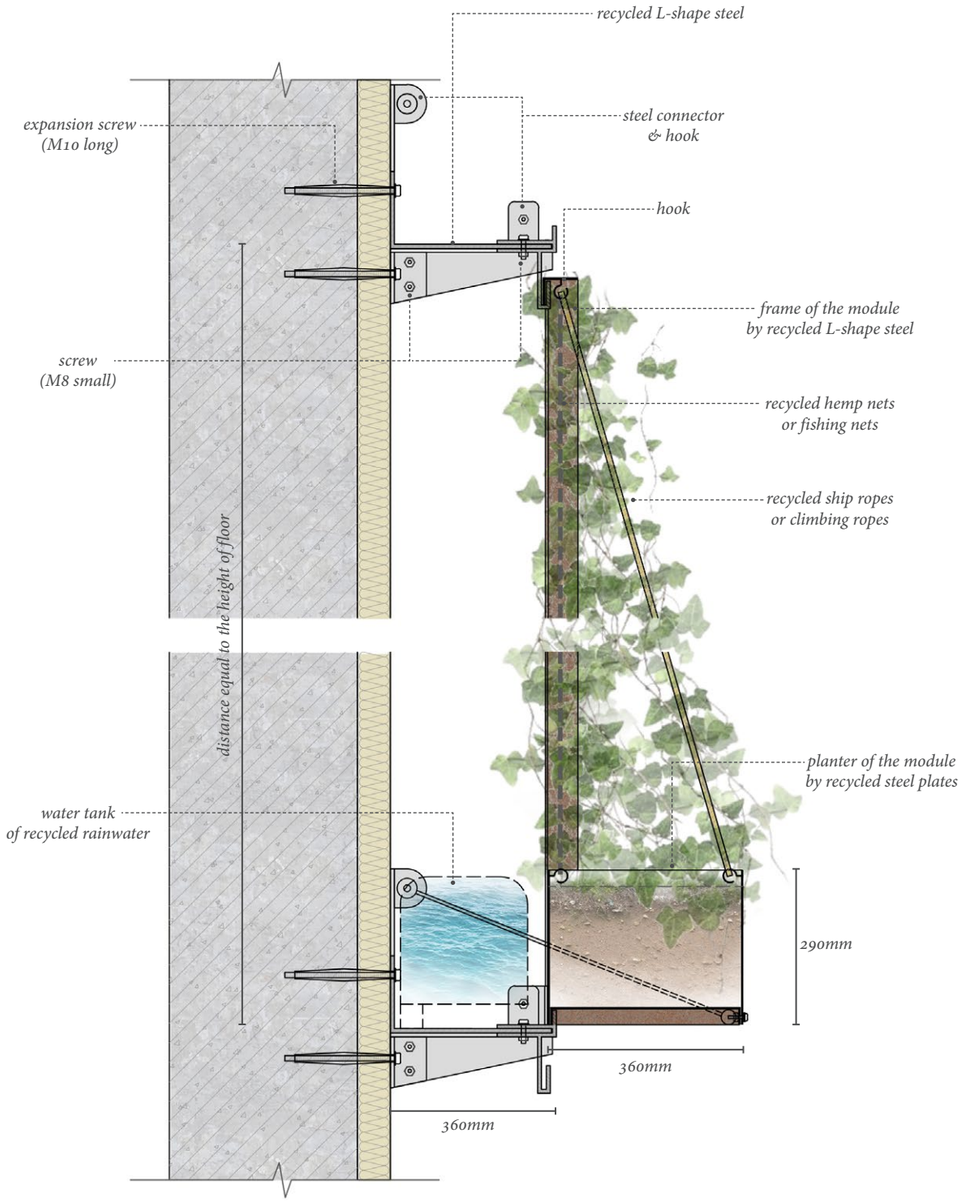


Illustration 38. Vertical section of wall

Beacause the facade is to the south, the plants should be full-sunlight tolerance and like to grow under full-sunlight or partial-sunlight condition. Moreover, wind tolerance is also important for the plants, because, during over 30% days of a year, wind is from the south. In this module system, the plannts do not need strong-climbing ability, but they should be drought-tolerant and poor-soil tolerant. The suitable climbers are Euonymus fortunei and Climbing rose.

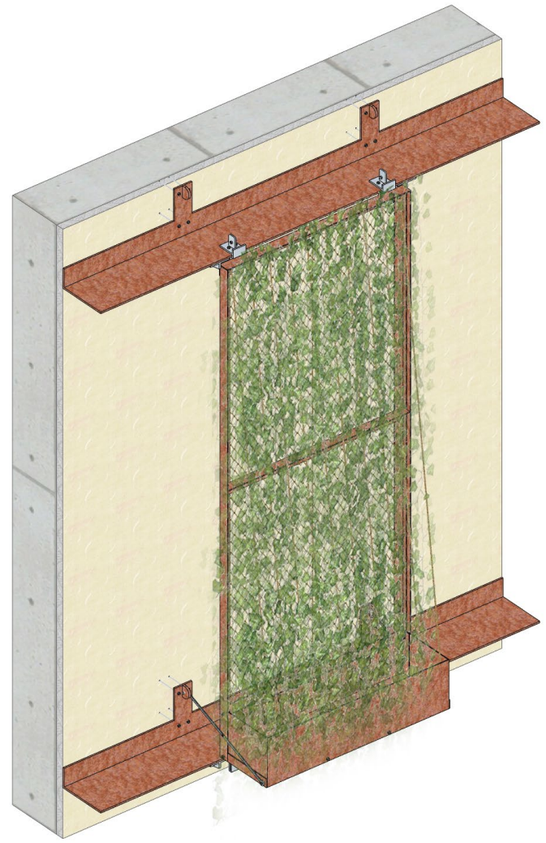


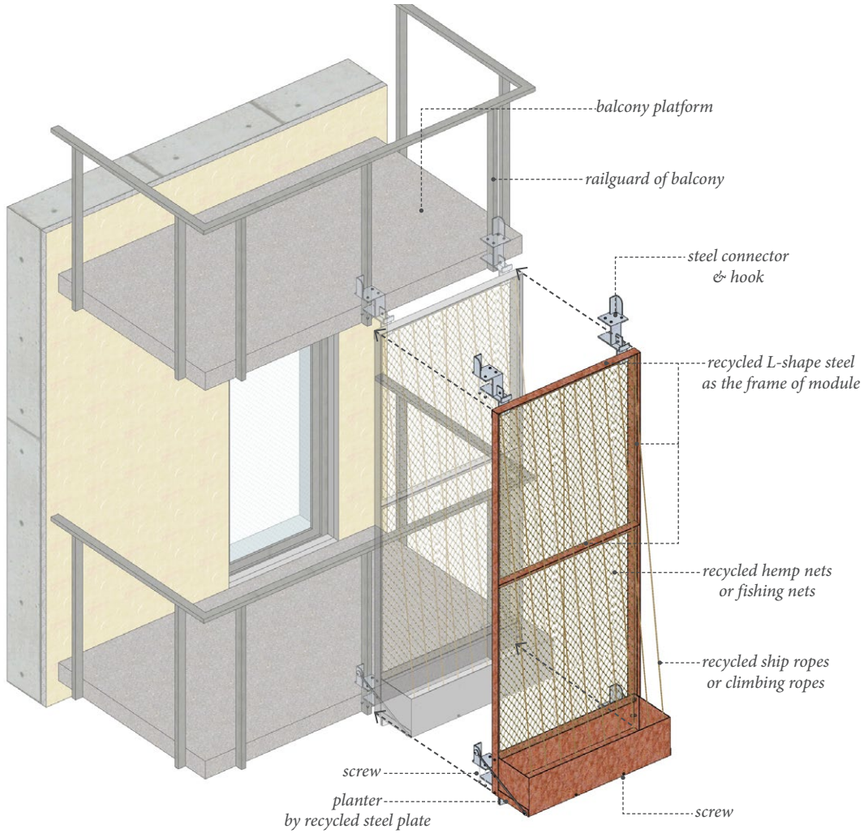
Illustration 39. Living wall planter module on foam wall

Suitable plants:

Euonymus fortunei

Climbing rose

The living wall planter module not only can be used on the wall but also on the balcony. It could be hanged and fixed between two vertical balconies. In this way, the module even does not need the automatic irrigation system, and the dwellers can help to water plants and do simple maintenance.



In this system, four steel connectors with hook are fixed on the platforms of the two next balconies. The module are hanged on the connectors, and fixed with them by screws.

Illustration 40. Construction of living wall planter module on balcony

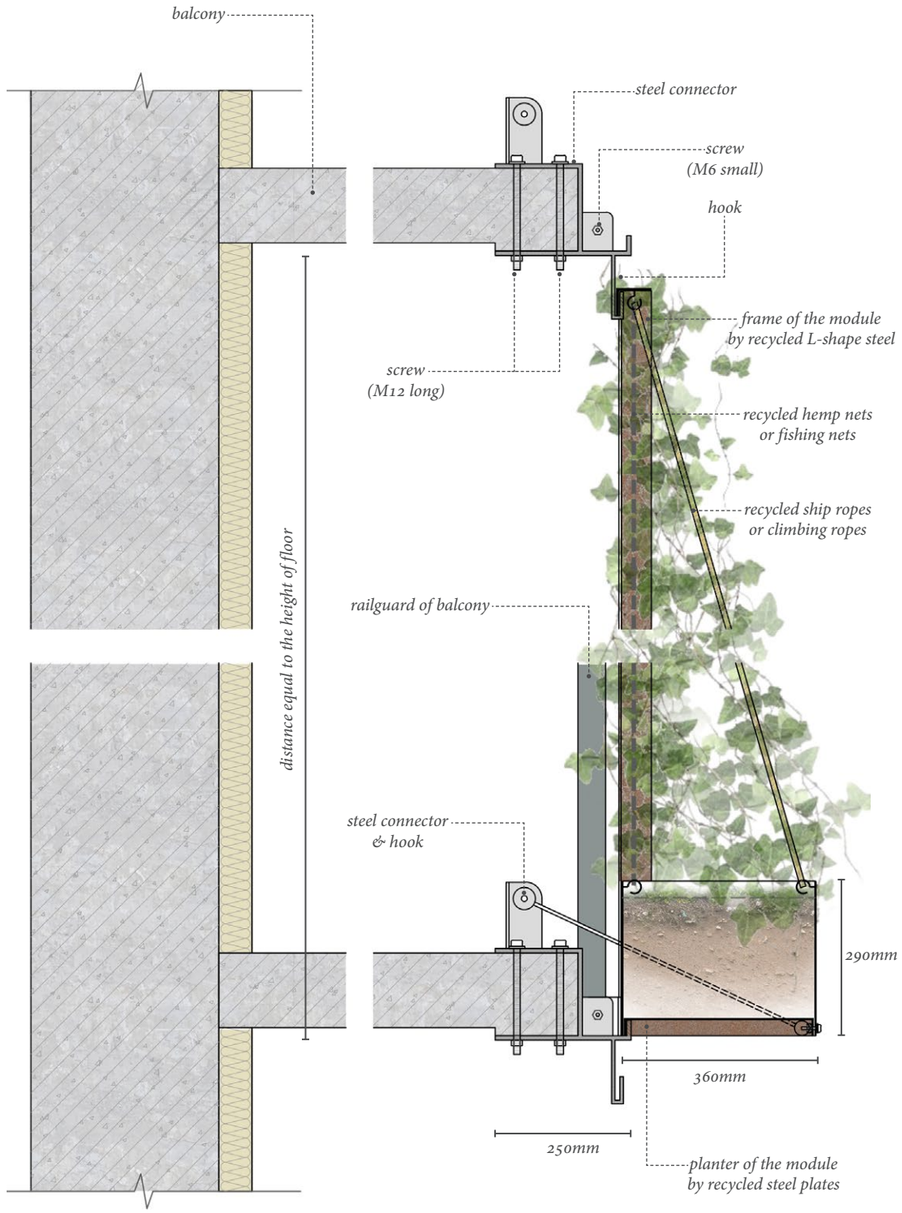


Illustration 41. Vertical section of wall

When the living wall planter module is used on balconies, it could be with the same climbers as the one used on walls. Moreover, it is better to choose the plants which will not be impacted a lot by human's touch and other daily activities. The plants should also have no toxic, no strong smell, and no allergic risk. If the insects are not interested in this kind of plant, it will be better to some dwellers. The suitable climbers are Euonymus fortunei. Hedera Helix is also a good choice for the module on balconies, but not the ones on southern facade.

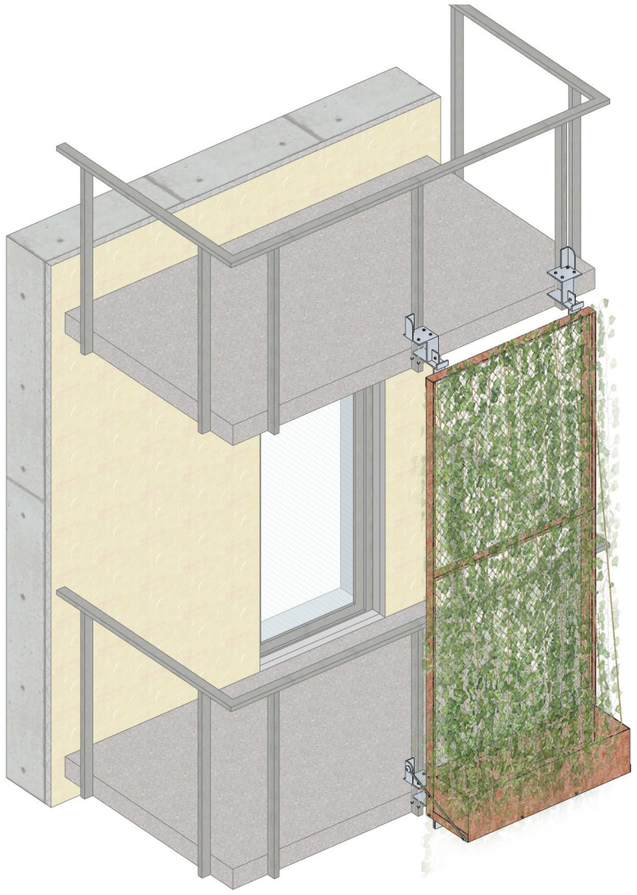


Illustration 42. Living wall planter module on balcony

Suitable plants:

Euonymus fortunei

Hedera helix

Design of the concrete facade building

As for this concrete facade, living wall planter module is a good solution for the balconies. This green system can be used as shading system for the building in the afternoon of summer. In hot days, more greening modules could be installed on balconies than in winter, thereby reducing more overheat. The residents could help to irrigate the green modules on their balconies, so there is no need of irrigation system for the plants. On the second floor, hanging plants is a suitable solution for the horizontal wall under the windows to generate a green hanging curtain. They can also be watered by residents through the windows.

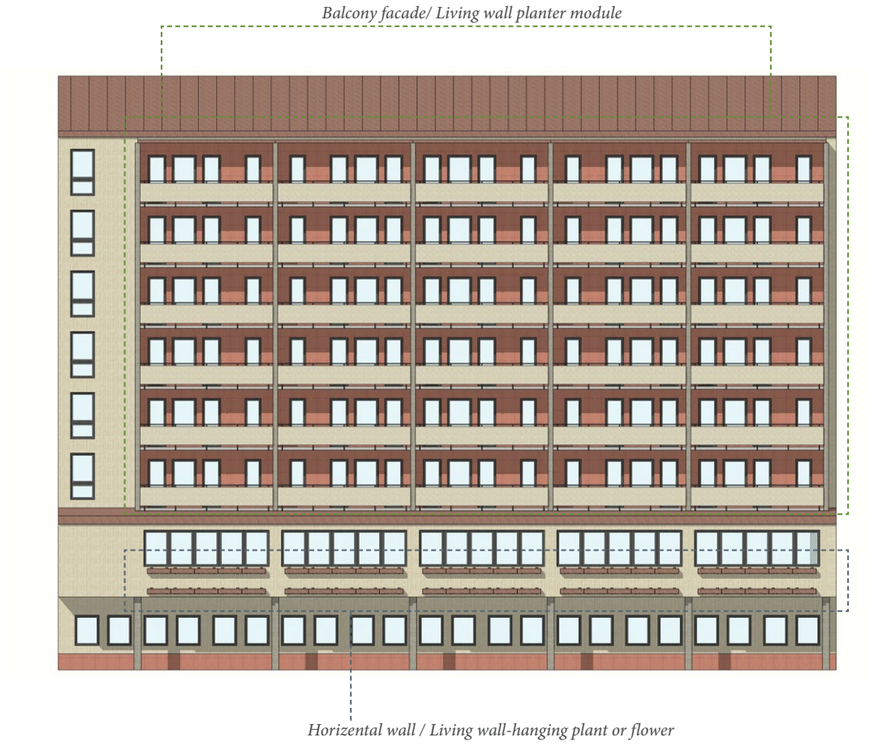


Illustration 43. Greening solutions for different facade conditions

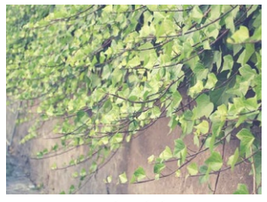
As for this building, it has a very interesting facade with balcony-matrix, which could provide portential for vertial greenery. With living wall module, it could show various green effects by arranging modules in different ways. Due to easy installment and disassemble, the greenery pattern can always be changed by a period of time. There are some examples in the following drawings.

Illustration 44. Facade greening effect by organized living wall modules

Illustration 45. Facade greening effect by changed living wall modules

Illustration 46. Facade greening effect by random living wall modules

This building facade faces to the west, which means it is under partial-sunlight condition in summer, and under partial-shade condition in other seasons. The west orientation also has the longest wind period during a year. Therefore, Hedera helix and Climbing rose are suitable climbers for the living wall planter module. In terms of the hanging plants, Lysimachia nummularia and Vinca minor could be the suitable choice to generate a green hanging curtain.



Hedera helix

Climbing rose

Lysimachia nummularia

Vinca minor

Conclusion

This thesis is about the research on façade greening of existing residential buildings in Gothenburg. The main object focuses on the medium-height houses, around 3 to 10 floors, in urban areas. Due to the huge amount of this kind building and their generally boring appearance, greening their facades can not only largely enhance the vegetation coverage in urban areas, but also help to upgrade their appearances. In addition, it is also an effective way to make up for the green-land loss brought by urban development and improve the degradation of eco-environment. The greenery could bring many benefits to cities, by improving the air quality, reducing the urban heat island phenomenon, helping on flood storage and humidity adjustment, absorbing urban noise, and enhancing biodiversity; moreover, the greenery also have positive influences on human's mental and physical health. As for the façade greenery, it can absorb over solar radiation for buildings, improve the thermal insulation property of building envelops, and protecting the façade materials from UV light; the façade greenery could also provide a new kind of city landscape.

In order to find suitable solutions for residential façade greening in Gothenburg, firstly, studies have been done on the conventional façade greening styles and the local context of Gothenburg. For example, in terms of the conventional greenery styles, what are the differences between them, what are their features, what are the suitable plants for different greening styles, what maintenance do they need. The research on the local context of Gothenburg is mainly about three aspects, the situation of different houses, the local climate and the suitable plants for vertical greenery in Gothenburg. In the next step, according to the different conditions of buildings, like height, orientation, façade material, maintenance, components and surroundings, the thesis firstly categories which kinds of buildings are suitable for greening and which kinds are not; and then, analyzing the influence of these parameters on façade greenery; at last, finding suitable strategies for different building conditions. When it comes to how to reduce the maintenance costs and enhance its sustainability, the thesis has discussions in three directions, material, irrigation and construction. As an industrial and harbor city, waste materials, like steels, ship ropes and fishing nets, are common in Gothenburg, and they can be reused as the supporting system of façade greenery. Rain is a kind of sufficient resource in Gothenburg, so recycling the rainwater in irrigation system and using its gravity as the main driving force are sustainable solutions. Finding simple and flexible methods of the construction could help to make the installation, replacement and maintenance of the greening system more easy, which means saving more time and money. After all the above research and analysis, in the final part, three local and typical buildings are chosen to test multiple greening solutions. According to their different conditions, different greening solutions are designed for them, with details, materials, construction and suitable plants. By combining different solutions together, various integrated façade greening projects could be generated.

The final results of this thesis are multiple façade-greening solutions, consisting of their own features and applicable conditions, constructions and details, materials, suitable plants, methods of installation, replacement and maintenance. In addition, because these solutions are designed for different building conditions, the thesis also shows that how to choose suitable solutions for different building conditions and climates.

In the process of the research, it is found that, in greening projects, there are many parameters which have influence on the success and sustainability of the greenery system, such as climate, building conditions, plants, maintenance, constructing styles, and so on. Therefore, in the design, it is very important for architects to have integrated and holistic analysis of all these parameters, thereby finding right solutions for different projects. In addition of this, the sustainability of greening projects is also important. It is not a right way of spending much water, energy or labor on the maintenance to make the system successful. Smart solutions can be found in the fields of recycled materials, rainwater reuse, simple and flexible construction, and of course, more other ways.

The greenery solutions designed in this thesis could bring many positive effects. For example, the green façade direct, indirect and living wall planter module on walls could help to reduce solar radiation on building facades in summer; the module on balconies and the hanging plants could be used as shading systems for windows. Suitable design of these greening systems on the facade can not only improve the aesthetics and ecology of the facade, but also help the building control overheat in summer. In addition, these green solutions can also help improve building microclimate, purify the air, reduce urban noise, enhance urban biodiversity and be beneficial to human health. However, because measuring the specific degree of these influences needs professional simulation or experiment, these issues will not be discussed in this article. They will be interesting topics in further research.

Humidity problem caused by the greenery systems may have negative impacts on the materials and structure of the building façade. Therefore, for the façade materials which are prone to be impacted by humidity issue, like plastic foam, it is better to keep suitable distance between the greenery system and the wall for enough ventilation. In addition, choosing durable materials for the greenery supporting system, and making waterproofing for necessary parts can also help with the humidity issue.

Most of the suitable plants for the greenery solutions in this thesis are evergreen, which means they can provide green effects for the building the whole year. Moreover, in spring and summer, some plants will have beautiful flowers; in autumn, the leaves of some plants will change the color.

In this thesis, some solutions could be watered and pruned by residents, like living wall planter with hanging plants or flowers, living wall planter module on balconies. This is beneficial to reducing the cost of regular maintenance, but it needs clear and organized maintenance plans for these plants and effective cooperation with the residents.

The greenery solutions in this thesis could also be used in other regions around the world, like some seaside cities in the north China. These cities have similar climate with Gothenburg in autumn and winter, and most of the residential facades are in the materials of brick, concrete or plastic foam. However, it is still crucial to analyze the local climate and context. According to the specific conditions, making suitable adjustments for the greenery solutions.

At last, there are also some other issues found during the research. These issues have not been discussed in the thesis, but they deserve to be studied in the further work. For example, the climbing plants can always generate green curtains on facades, which means they have opportunities to be used as kind of shading stuffs for houses; therefore, it will be a very interesting topic that how to use vertical greenery as shading system on building facades, by which kinds of plants, what construction systems, what relation between plants and facades, what density and size of the plants, how about different orientations. Another topic is that how to use different kinds of plants in one façade-greenery project, in order to achieve more vivid and diverse landscape, and how to make different views in different seasons. At last, how to let the green facades to be not only the view for the city but also the landscape for dwellers and part of their daily life. All these questions deserve to be researched more in the next step.

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