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Green façades and building structures

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M&E

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Preface

The presented study is a master thesis, which belongs to the subject CIE5060 of Faculty of Civil Engineering of Delft University of Technology. The master thesis is the graduation project. The report gives an overview of different vertical greening systems, building physical aspects of vertical greening systems and a life cycle analysis (LCA) is conducted for two living wall systems. The different vertical greening systems studied in this project are compared with a traditional non greened façade (bare wall) related to building physical aspects and a life cycle analysis.

This graduation project is linked to the PhD research (Ottelé, 2011. The green building envelope) which is a further elaboration of vertical greening research.

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Ashraf Mir, BSc.

Samenvatting

Planten kunnen verschillende functies vervullen. Planten bieden mogelijkheden voor spelen, sport en recreatie, tot stand brengen van sociale contacten, ontsnappen uit het stadsleven, esthetisch genot en etc. Vegetaties en planten op daken en gevels van gebouwen is een snel ontwikkelend gebied op basis van duurzame technologie met betrekking tot de bebouwde omgeving en tuinbouw.

Dit rapport bevat een algemene beschrijving van verticale groen systemen (planten of vegetaties tegen een gevel) en hun gedrag in relatie tot verbetering van de luchtkwaliteit, esthetiek, energie besparing, biodiversiteit, vermindering van het stedelijk heat island effect (UHI) en de sociale gevolgen er van. Verticaal groen in relatie tot vochttransport door muur constructies en een leven cyclus analyse (LCA) voor twee living wall systemen zijn uitgebreid toegelicht.

Verticaal groen is op dit moment een populair item van duurzame ontwikkeling voor een beter milieu in relatie tot dicht bebouwde stedelijke gebieden. Verticaal groen kan opgedeeld worden in drie hoofd takken, namelijk:

- *groene gevels;* (traditionele gebruik van klimplanten tegen een gevel uit de grond of uit plantenbakken), zijn de gemakkelijkste en goedkoopste manier om de verticale oppervlakken met vegetaties te bedekken. De beschikbare groene gevels op dit moment kunnen worden ingedeeld in twee hoofd categorieën namelijk: planten uit de grond en planten uit plantenbakken op verschillende niveaus. Groene gevels zijn begroeid door klimplanten welke rechtstreeks tegen een muur groeien of indirect met een speciale hulpconstructie zoals kabels, net systeem of gaas. Heel veel verschillende klimplant soorten kunnen als groen gevel toegepast worden. Hedera planten zijn de meest voorkomende planten in de praktijk.

- *muurvegetaties;* (spontane groei van planten op constructies), groeien zonder enige menselijke tussenkomst op een natuurlijke manier met onregelmatige patronen. Muurvegetaties groeien vooral in oudere gebouwen en monumenten. Betonpanelen met grote poriën tussen de grindkorrels is een nieuwe ontwikkeling voor het maken van verticale groen constructies, welke ook onder deze verdeling valt. De poriën worden met grond gevuld en de planten kunnen tussen de poriën inwortelen. Deze panelen kunnen als gevel elementen worden toegepast. De planten krijgen water uit natuurlijke bronnen zoals regen en etc.

- *living wall systemen (LWS);* (voorbegroeide "prefab" modulaire panelen of in situ toegepaste panelen), is een relatief nieuwe toepassing van verticaal groen met een nieuwe technologie. Een water-geef systeem met een voeding system is altijd nodig om de living wall systemen in leven te houden. De modulaire panelen zijn vervangbaar en verplaatsbaar. Er zijn verschillende soorten van living wall systemen die al toegepast zijn of in de toekomst worden toegepast. Bij living wall systemen groeien de vegetaties niet uit de grond maar in een substraat die als panelen op de muur gevestigd zijn. Dit vormt de grote onderscheiding met groene gevels. Living wall systemen kunnen zowel binnen als buiten worden toegepast. Een paar living wall systemen die in dit rapport worden beschreven, zijn LWS op basis van plantenbakken, LWS op basis van schuimsubstraat, LWS op basis van minerale wol en LWS op basis van vilt lagen.

Verticaal groen systemen hebben net als andere gevel systemen een aantal voor- en nadelen, die hieronder worden samengevat.

De voordelen van verticaal groen systemen zijn onder andere:

- het filteren van de fijn stof deeltjes uit de lucht om de luchtkwaliteit te verbeteren.
- het verminderen van de stedelijke heat island effect (UHI).
- het bieden van geluidsisolatie.
- het tot stand houden van interne temperatuur in een gebouw via externe zonwering.
- het creëren van een microklimaat.
- het creëren van biodiversiteit en een natuurlijke leefomgeving voor dieren.
- het beschermen van de muur tegen graffiti.
- het verbeteren van de isolatie eigenschappen van de gebouwen in zomer en winter.

De nadelen van verticale groen systemen zijn onder andere:

- kans op schade aan bestaande gevel (gescheurd) in geval van klimplanten direct aan de muur.
- het onderhouden van verticaal groen systemen.
- kosten van verticaal groen systemen, vooral living wall systemen.
- irrigatie of water-geef systemen.

Voor het vergaren van meer wetenschappelijke informatie, is een experimentele opstelling (hotbox) gemaakt om een aantal verticale groen systemen te testen en te meten hoe het vochttransport door het verticaal groen system naar de muur plaats kan vinden.

De hotbox is van multiplex (dikte 18 mm) en EPS-SE isolatiemateriaal (dikte 200 mm) gemaakt. De hotbox heeft een afmeting van (3000 mm x 1800 mm x 1800 mm) en heeft twee compartimenten voor binnen en buiten klimaten. Het principe van het testen in de hotbox is om onder steady-state omstandigheden (stationaire laboratorium conditie) vochttransport door een verticaal groen systeem die aan een proefstuk (kale muur) hangt, te bepalen. Proefstuk is tussen een warme en een koude klimaatkamer geplaatst en in verschillende klimatologische omstandigheden (zomer en winter) gemeten. Het proefstuk dat voor het experiment gebruikt wordt, bestaat uit een muur met een oppervlakte van 1 m^2 (gemaakt volgens Nederlands bouw normen). Het proefstuk is als volgt gemaakt: (binnen blad + isolatie + luchtspouw + buiten blad). De metingen in de hotbox zijn met thermokoppels en hygrometers uitgevoerd welke door het hele systeem (kale muur + verticaal groen) plaats heeft gevonden.

Zoals het eerder al vermeld is, het gedrag van verschillende verticale groen systemen volgens bouwfysica en duurzaamheids aspecten worden ook in dit rapport besproken. In een aantal experimenten, een aantal verticale groen systemen (*Hedera helix* direct aan de muur, *Hedera helix* indirect aan de muur, LWS op basis van plantenbakken, LWS op basis van schuimsubstraat, LWS op basis of minerale wol en LWS op basis van vilt lagen) zijn getest en gemeten in een proefopstelling (Hotbox).

De resultaten van de uitgevoerde metingen laten zien dat de verticale groen systemen (*Hedera helix* direct aan de muur, *Hedera helix* indirect aan de muur en LWS op basis van plantenbakken) welke voor het bepalen van het vochttransport berekend zijn, hebben geen negatieve invloed met betrekking tot vochttransport en condensatie op het oppervlak van de muur. Het is duidelijk geworden dat de verticale groen systemen op de gevels in de winter condens kunnen veroorzaken. De zomer metingen tonen aan dat met een normale relatieve vochtigheid van ongeveer 75% geen condensatie kan optreden in alle lagen van de constructie. Bij alle metingen met temperaturen onder het vriespunt kan condensatie optreden. Volgens Glaser methode wordt de condensatie in alle gevallen niet groter dan wat is toegestaan. Dit betekent dat het opgenomen vocht door de constructie in de winter (60 dagen) terug moet verdampen in de zomer (90 dagen).

Er is geen dampdiffusieweerstand getal (μ) voor verticale groen systemen in de literatuur, en daarom is het nodig om een dampdiffusieweerstand getal (μ) voor de verticale groen systemen aan te nemen om de condensatie berekeningen te kunnen uitvoeren. Voor alle condensatie berekeningen met betrekking tot verticaal groen een dampdiffusieweerstand getal (μ) van 1,5 wordt aangenomen. Dit komt overeen met de in literatuur vermelde waarde van ($\mu \geq 1$). Het is belangrijk te noteren dat de relatieve luchtvochtigheid binnen en buiten, type verticaal groen systeem, binnentemperatuur en buitentemperatuur een belangrijke rol spelen bij het bepalen van de condensatie en dampdiffusie. Living wall systemen hebben een min of meer lucht dichte structuur en dat zorgt ervoor dat de gevels tegen directe zon en regen beschermd blijven. De gebruikte materialen voor living wall systemen kunnen ervoor zorgen dat het vochttransport niet gemakkelijk plaats vindt.

Voor het bouwen van verticale groen systemen, is het noodzakelijk om te weten dat de productie van ondersteunende hulpmiddelen negatieve milieu effecten kunnen hebben welke in strijd kan zijn met duurzaamheid. Duurzaam bouwen kan als een manier van ontwerpen en bouwen worden omschreven, die ondersteuning biedt voor de menselijke gezondheid (fysiek, psychisch en sociaal) en die in harmonie met de natuur blijft. Een systeem is duurzaam als de milieubelasting lager is dan het milieu voordeel profiel. De resultaten van de uitgevoerde levens cyclus analyse (LCA) voor living wall systeem op basis van minerale wol en living wall systeem op basis van schuimsubstraat geven inzicht in de milieu impact van de bestudeerde living wall systemen.

- de LWS op basis van minerale wol heeft een hoge milieu belasting als gevolg van de gebruikte materialen. De aluminium draagstructuur vormt grotendeels de hoge milieu belasting, terwijl de andere materialen de thermische weerstand van het systeem positief kunnen beïnvloeden.
- de LWS op basis van schuimsubstraat heeft ook een grote invloed op het totale milieu belasting, maar het schuimsubstraat zelf is een afbreekbaar en duurzaam product.
- voor de living wall systeem op basis van minerale wol en living wall systeem op basis van schuimsubstraat in beide klimaat types (mediterrane en gematigd), de milieu belasting profiel is hoger dan de voordelen voor verwarming en koeling.
- zowel LWS op basis van minerale wol en LWS op basis van schuimsubstraat leveren bijna dezelfde bijdrage aan de energie besparing voor de verwarming. Maar voor het mediterrane klimaat, kan een hogere invloed voor de koeling eigenschappen van de planten worden genoteerd, welke te herkennen is voor alle 6 verticale groensystemen die in de hotbox zijn getest.

Summary

Plants can fulfil various functions. Plants provide places for playing, sports and recreation, establishing social contacts, isolation and escape from urban life, aesthetic enjoyment, viewing buildings from a distance and so on. Vegetation and plants on roofs and façades is one of the functions of plants most with respect to the built environment and horticulture. The presented report contains a general description of vertical greening systems (plants or vegetations against a façade) and their behaviour in relation to air quality improvement, aesthetics, energy saving, biodiversity, mitigation of the urban heat island effect and its social impact. Vegetation in relation to moisture transport and a life cycle analysis (LCA) for two living wall systems are particularly extensively explained.

Vertical green or "green walls" is at the moment a popular item of sustainable development for a better environment related to dense urban areas. Vertical greening can be divided in three main branches, namely:

- *green façades;* (traditional use of climbing plants against a façade from the ground or from planter boxes), are the easiest and cheapest manner to cover the vertical surfaces with vegetations. Green façades that are available until now can be classified in to two main categories, namely plants rooted into the ground and plants that are rooted in artificial substrate at grade with watering system. Green façades can be applied directly to the wall and also indirectly to the wall with a supporting structure such as net system or cable and wire net system. A large variety of plants can be used for making green façades. Especially *Hedera* plants (common ivy) are the most common ones.

- *wall vegetations;* (spontaneous growing of plants on structures), are growing without any human intervention in a natural way with irregular patterns. This type of vegetation can be typically found on older buildings and monuments. Concrete panels with large pores variety are a new development to create green structures within a short period of time (1-2 years). These panels are also a type of façade which are suitable to plant vegetation on them.

- *living wall system (LWS);* (pre-vegetated "prefabricated" modular panels or in situ applied panels), is a relative new application form of vertical green using modern technology. A watering system and nutrients distribution are always required and the modular panels are replaceable. There are various types of living wall systems which are already applied and applicable. Living walls are distinct from green façades in that they support vegetation that is rooted in substrate attached the wall itself, rather than being rooted at the base of the wall, and as a consequence have been likened more to vertical living systems. Living wall systems can be used either outdoor or indoor. A large verity of plants as herbs can be used on the living wall panels. A few examples of living wall systems that are described in this report are LWS based on planter boxes, LWS based on foam substrate, LWS based on mineral wool and LWS based on felt layers.

Vertical greening systems have a range of advantages and disadvantages, which are summarized below.

Advantages of vertical greening systems include:
- filtering air particulates to improve air quality.
- reducing (mitigate) the heat island effect (UHI).
- providing sound insulation.

- moderating a building's internal temperature via external shading.
- creating a microclimate, which will help to alter the climate of a city as a whole.
- providing biodiversity and a natural animal habitat.
- protecting the wall against graffiti.
- improving the insulation properties in summer and winter.

Disadvantages of vertical greening systems include:
- chance of damage on façade in case of green façade directly to the wall.
- maintenance of vertical greening systems.
- costs of vertical green systems, especially living wall systems.
- irrigation systems.

An experimental setup called 'hotbox' is made to test a number of vertical greening systems to determine the moisture transport through it. The hotbox is made of plywood (thickness 18 mm) and EPS-SE insulation material (thickness 200 mm). The hotbox has a dimension of (3000 mm x 1800 mm x 1800 mm) and has two compartments for indoor and outdoor climates. The principle of testing in the hotbox is to determine under steady state conditions (laboratory condition) moisture transport through a test specimen (bare wall) placed between a warm and a cold enclosed enclosure and to compare this with vertical greening systems hung on the wall under a variety of climate conditions (summer and winter). The test specimen used for the experiment consists of a wall with a surface of 1 m^2 (made in Dutch building system). The test specimen has a (inner leaf + insulation + air cavity + masonry). The measurements are performed with thermocouples and hygrometers through the complete system of a bare wall with greening systems on it.

As it is mentioned the behaviour of different vertical greening systems according to building physics and sustainability aspects are also discussed in this report. A start was made to determine the black spots within the thermal behaviour aspects of vertical greening systems. In a number of experiments some vertical greening systems (*Hedera helix* directly to the wall, *Hedera helix*, indirectly to the wall, LWS planter boxes system, LWS foam based system, LWS mineral wool based system and LWS felt layers system) have been tested in a test setup called 'hotbox'.

The results of the performed tests show that the vertical greening systems which are calculated for determining of moisture transport (*Hedera helix* directly to the wall, *Hedera helix* indirectly to the wall and LWS based on planter boxes) have no negative influence with respect to moisture transport and condensation on the surface of the wall. It became clear that vertical greening systems on the façades in the winter cause condensation. The summer measurements show that with a normal relative humidity of about 75% the condensation cannot take place in any layer of the structure. Condensation is occurred at all measured greening systems with freezing temperatures. According to Glaser method the condensation in all cases does not exceed the limitations. This means that the absorbed moisture by the structure in the winter (60 days) should evaporate back in the summer (90 days). There is not a vapour diffusion resistance figure (μ) for greening systems in the literature and therefore it is needed to assume a vapour diffusion resistance figure (μ) for vertical greening systems to calculate the condensation. For all condensation calculations a vapour diffusion resistance figure (μ) of 1.5 is assumed for vertical greening systems, which corresponds with the regulations that ($\mu \geq 1$). It is important to notice that the relative humidity outdoor and indoor, vertical greening system type, outdoor and indoor temperatures play a major role in determining of condensation and vapour diffusion. Living wall systems have a more or less airtight texture and they are protecting the façade better against direct sunshine and (heavy) rains. The materials used for living wall systems can ensure that the moisture transport does not take place easily.

To realize vertical greened surfaces, it is necessary to take in to account that manufacturing of for example supporting structures can have a negative environmental effect, which is in struggle with sustainability. Sustainable construction could be described as a way of designing and constructing building that support human health (physical, psychological and social) and which is in harmony with nature, both animate and inanimate.
A system is sustainable when the environmental burden is lower than the environmental benefit profile. The results from the conducted life cycle analysis for living wall system based on mineral wool and living wall system based on foam substrate provide insight in the environmental impact of the studied vertical greening systems.

- the LWS based on mineral wool has one of the high environmental burdens due to the materials used. The aluminium supporting structure forms largely the effect since the materials affect positively the thermal resistance of the system.
- the LWS based on foam substrate has also high influence on the total environmental burden, but the foam substrate (biodegrable) itself is a sustainable product.
- for the living wall system based on mineral wool and living wall system based on foam substrate in both climate types (Mediterranean and temperate) the environmental burden profile is higher than the benefits gained for heating and cooling.
- both LWS based on mineral wool and LWS based on foam substrate have almost the same contribution to the energy savings for heating but, for the Mediterranean climate, a higher influence was noted for the cooling properties of the plants which are to recognise for all 6 vertical greening system tested in hotbox.

1 Introduction

1.1 General

Nowadays architects and engineers try to design and build environmental friendly as much as possible. Urban developers are currently searching for areas to plant vegetation. Hence, the greening of the façade of building walls, known as vertical greening systems, is gaining in popularity (Wong et al., 2009). According to Yu-Peng yeh (2010), the colour green can bring harmony to people's mind. People living or working in cities especially need to slow down their fast-paced life through looking at green plants. The widespread use of vertical greening systems on the numerous building walls in cities not only represents a great potential in reducing urban noises generated from traffic and machines, it is also a highly impactful way of mitigating the urban heat island effect (UHI) and transforming the urban landscape (Wong et al., 2009). According to literature green claims to have many benefits such as aesthetics, energy saving, air quality improvement, decreasing of the temperature and a sound insulation character (Bioscience, 2007).

Many researches are carried out, to increase knowledge about the effects of greening urban areas, but still more researches should be done about new applications for green facilities. To quantify and to get more insight in the benefits of vertical green more research is needed to falsify the claims that are made in history. Land becomes expensive in urban areas and there is not enough space to create green facilities. With other words this means that lack of available spaces is a large problem for urban green applications.

To solve this problem inside dense cities, greening of buildings (green façades and roofs) can be a promising option to fulfil the shortage of urban green. Roof gardens and green façades, though not a new concept, increase the percentage of greenery in urban built-up area and bring back the vanishing urban green space (Wong et al., 2003).

This chapter describes the research objectives and gives an introduction of vertical greening systems. To narrow down the scope of this vertical green research, it is tried to give a clear overview of vertical green concepts and their characteristics with a general description of vertical greening systems (green walls, green façades) and their forms of application in chapter 2. Chapter 3 describes the advantages and disadvantages of vertical greening systems with respect to aesthetics, air quality, thermal behaviour, social aspects, etc. The building physical measurements of different green walls in a test setup called 'hotbox' as a part of the vertical green research are included in chapter 4 and 5. Moreover, life cycle analysis (LCA) applications on vertical greening systems which are available in the Netherlands market, is the subject of chapter 6. Chapter 7 shows a decision tree which can lead to choose the appropriate vertical greening system for applying on different buildings. The conclusions and recommendations are included in chapter 8.

1.2 Research objectives and research question

To understand and get more insight in vertical greening systems and their forms of application in practice, a comparison between a bare wall and vertical greening systems is advisable. To determine temperature and moisture transport through vertical greening systems combined on façades in various (summer and winter) conditions, an experimental research (Ottelé, 2011) was carried out, in which different vertical greening systems are tested and measured. This MSc. graduation project continuous with the experimental research.

The objective and the main question of the experiment in this research project is, to know and recognise if there is any influence of vertical greening systems on a wall with respect to moisture transport and condensation compared with a bare wall. Besides, the sustainability aspects of vertical greening systems will be investigated for some living wall systems (LWS based on mineral wool and LWS based on foam substrate). This will be carried out with a LCA methodology to examine the overall environmental impact of the products throughout their entire life cycle. A decision tree is built up to choose the right vertical greening system for a possible façade design.

Given the subject studied, some sub questions can be formulated:

- *Which vertical greening systems exist, and what are their configurations?*
- *What are the advantages and disadvantages of vertical greening?*
- *What is the contribution of vertical greening systems on moisture transport compared with a bare wall (non greened façade)?*
- *What are the effects of vertical greening systems with respect to moisture problems?*
- *What are the overall environmental impacts of living wall systems in terms of sustainability throughout their entire lifecycle?*
- *Which vertical greening system is advisable to use on existing or new structures?*

1.3 Introduction of vertical green

Since the beginning of human existence man has clearly intended to alter his microclimate, to a more "human friendly" one, protecting himself from extreme climatic conditions. Even from the first evidence of Neolithic houses and settlements, it is obvious that they were not sited in a purely natural environment, but in a part of nature transformed according to a human plan (Benevolo, 1980). History shows that green façades were already present from the past (Köhler, 1993). People have always tried to give a beautiful image to the skin of buildings and other structures with usage of green on it. The famous hangings gardens of Babylon are the examples that can be mentioned. The gardens were probably developed on a structure like a ziggurat and built in the form of elevated terraces, so that the gardens were at different levels which grew around and on top of a building (figure 1.1).

Figure 1.1: impressive image of Hanging Gardens of Babylon (source: http://ancientworldwonders.com)

Plants can fulfil various functions. According to Givoni (1991), plants provide places for playing, sports and recreation, meeting establishing social contacts, isolation and escape from urban life, aesthetic enjoyment, viewing buildings from a distance and so on. It has been proved that visual and physical contacts with plants can result in direct health benefits. Plants can generate restorative effects leading to decreased stress, improve patient recovery rate and higher resistance to illness (Givoni, 1991). Green spaces in the living environment (focussed on urban areas) can be an important environmental factor, which can have influence to our health (van den Berg et al., 2010). But unfortunately because of increasing urbanization in the previous times a lot of people become more and more displaced from green areas. The unstoppable force of urbanization is consuming vast quantities of natural vegetation, replacing them with hard and low albedo surfaces.

In most urban spaces, appreciable amounts of vegetation exist mostly concentrated in parks or recreational spaces. Although parks manage to lower temperatures within their vicinity, they are incapable of thermally affecting the concentrated built spaces where people live, work and spend most of their urban lives (Santamouris, 2001 and Giridharam et al., 2004). By placing vegetation within the built space of the urban fabric, raised urban temperatures can decrease within the human habitats themselves and not only in the detached spaces of parks (Alexandri et al., 2006). These changes result in the thermal properties of surfaces materials and the lack of evapotranspiration in urban areas lead to a phenomenon known as the urban heat island (UHI) effect (Wong et al., 2009).

Recently architects and responsible agencies are trying to create green spaces around the residence area, and they are searching for new configurations of green. According to Köhler, (2008) green can be applied on different manners in urban areas. Since the outer surfaces of buildings offer a great amount of space for vegetations in urban cities, planting on roofs and walls has become one of the most innovative and rapidly developing fields in the worlds of ecology, horticulture and the built environment (Wong et al., 2009).

Nowadays vertical greening (living wall systems) can be applied as a new technology and also offer many benefits as a component of our current urban design (Köhler, 2008). The simplest and cheapest way to apply vertical green is to plant climbing plants (for example common ivy) against the façade due to the adhesive character of these plant species. Greening of façades or in short 'Vertical green' is one of these multifunctional applications of urban greenery. The following diagram (figure 1.2) shows the vertical greening systems, which are available and already adopted at the moment based on literature and practice.

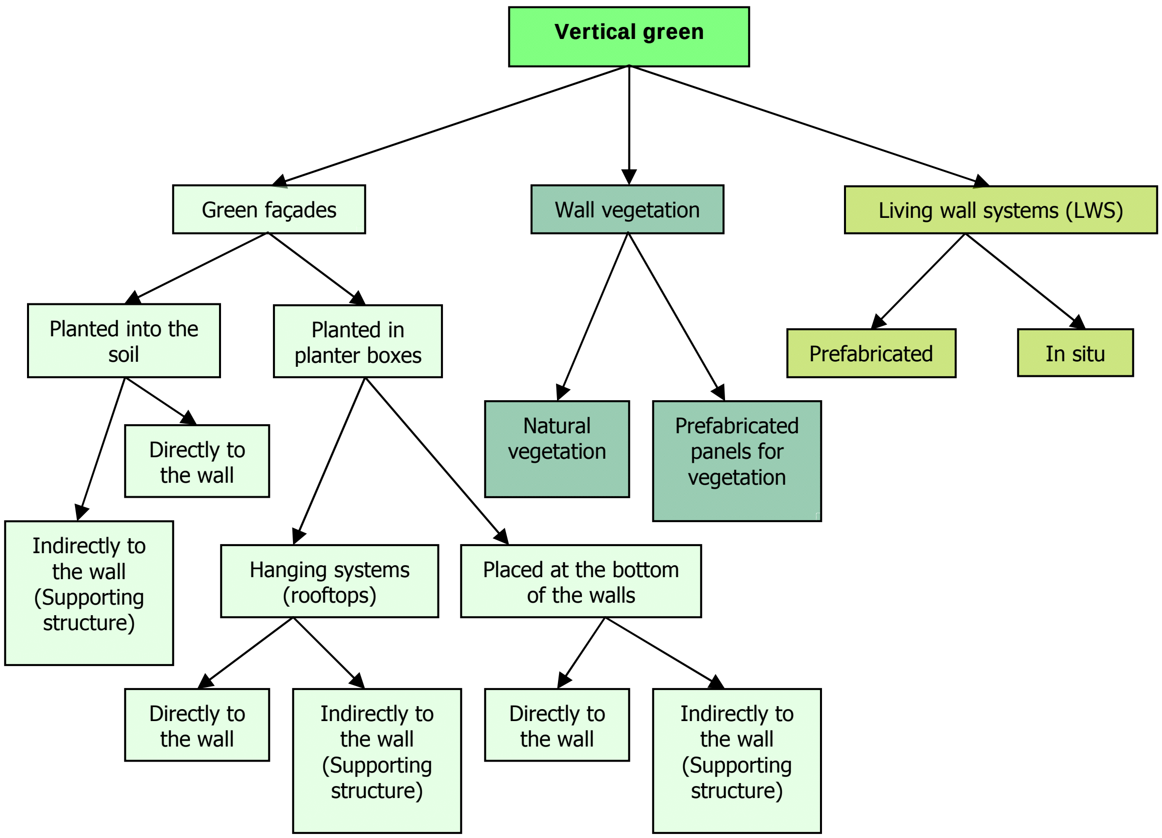


Figure 1.2: diagram of vertical greening systems based on literature (Krusche et al., 1982; Köhler, 1993; Hermy et al., 2005; Ottelé, 2011).

2 Vertical green

2.1 What is vertical green?

Vertical green, also commonly referred to as a 'Vertical Garden' is a descriptive term that is used to refer to all forms of vegetated wall surfaces. It is also called a system to attach plants to civil engineering structures and walls of buildings or vertical greened façades are walls that are either partially or completely covered with vegetation, and they have exuberant green looks (Yu-Peng yeh, 2010). Green or greened façades typically feature woody or herbaceous climbers either planted into the ground or in planter boxes in order to cover buildings with vegetations. Supporting systems are sometimes necessary and planter boxes can require specific growing media, much like green roofs, or supplemental irrigation. Annual maintenance is necessary to promote plant survival and growth at the façade (Köhler, 2008). Living wall systems (LWS) involve planter boxes or other structures to anchor plants that can be developed into modular systems attached to walls to facilitate plant growth without relying on rooting space at ground level. This technology is most closely allied with green roofs and allows a greater variety of plant growth forms than green façades (Köhler, 2008).

2.2 Description of vertical green systems

As explained in paragraph 1.3, vertical green can be applied in different forms. It is possible to divide vertical greening systems according to their structure, growing substrate, plant species and watering system if necessary. After a comprehensive literature study, vertical green can be divided into three different main categories:

1) Green façades
2) Wall vegetation
3) Living Wall Systems (LWS)

2.2.1 Green façades

Vertical greening is the concept of applying vegetation on vertical surfaces (façades). Green façades are walls that are covered with climbing plants or cascading vegetations. Green façade is the easiest and simplest application of vertical green. Green façades that are available on the market until now can be classified in to two main categories, namely plants rooted into the soil and plants that are rooted in artificial substrate at grade. The categories and the systems will be described step by step according to the diagram in figure 2.1.

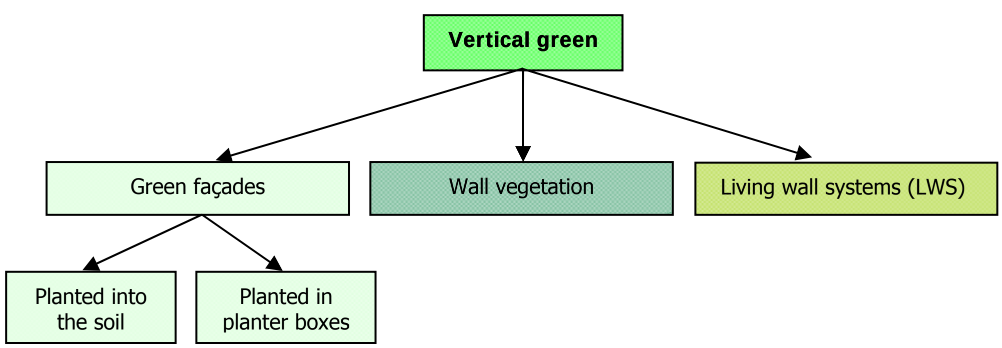


Figure 2.1: diagram of the basic vertical greening principles.

Categories:

a) plants planted into the soil.
b) plants planted in planter boxes.

a) Plants planted into the soil

The plants have their roots in the ground and allowed to grow from the soil against the façades. Plants grow in a natural way directly against the façade without the use of supporting systems. This type of green façade takes relatively a long time (years) to cover the whole surface of a wall (depending to the sizes of the wall and the amount of planted species). There is no watering system required, because the plants take water from natural sources like rainwater and groundwater. The category can be divided into self-climbing plants system (directly to the wall) and plants which need a supporting structure (indirectly to the wall). Figure 2.2 shows the principle of self climbing plants directly and indirectly to the wall. Figure 2.3a and b show some examples of this greening method.

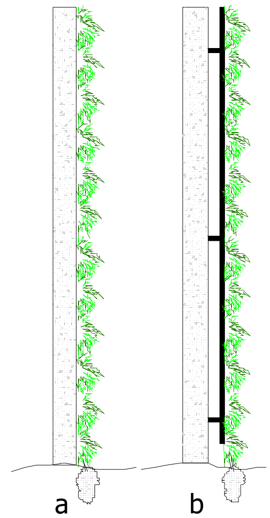


Figure 2.2: principles of plants rooted into the ground; use of self-climbing plants, (a) directly to the wall; (b) indirectly to the wall (with supporting structure).

Figure 2.3a: different green façades with self-climbing plants directly to the wall (source: left, www.groenedaken.mht and right, www.greenscreen.com).

Figure 2.3b: different green façades with self-climbing plants directly to the wall; left, Dordrecht; right library building in Sliedrecht.

The adhesive root structure enables to attach the plants directly to the façade, covering entire surfaces (figure 2.4). It is depending of the plant species used, how efficient the façade will be covered, how long (years) it takes to cover the complete surface of the façade and how many plants should be used in a certain distance with a certain space between the plants.

Figure 2.4: sucker root structure of plants directly to the wall (source: Minke and Witter 1982).

Not all plants species have adhesive properties to attach themselves to the façade and to grow directly on the façade. For these plant species, specially designed supporting structures (figures 2.5a and b) can be applied in order to make it possible to let the plants grow through the structure and cover the façade.

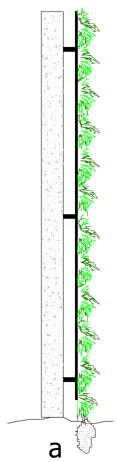


Figure 2.5: (a) the principle of plant on supporting structure; (b) specially designed supporting structures (source: www.greenscreen.com).

The supporting structure gives the opportunity to the plants to grow further and develop their branches in the vertical direction (figure 2.6).

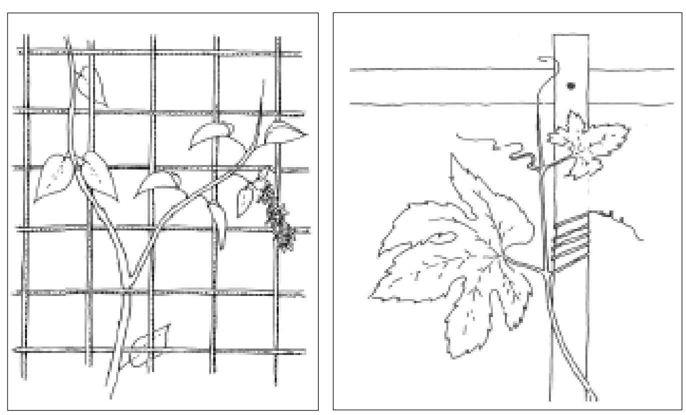


Figure 2.6: simply supported structures (source: Minke and Witter 1982)

At the moment there are two frequently used supporting structure systems for greening façades (www.greenroofs.org). The supporting systems can be divided into meshes and rope systems. The commonly based supporting systems are:

- modular trellis panel system
- cable and wire-rope net systems

Modular trellis panel system

The building block of this modular system is a rigid, light weighted, three dimensional panel made from a powder coated galvanized and welded steel wire that supports plants with both a face grid and a panel depth (figure 2.8a). This system is designed to hold a green façade off the wall surface so that plant materials do not attach to the building provides a 'captive' growing environment for the plant with multiple supports for the tendrils. It also helps to maintain the integrity of a building membrane (figure 2.8b). Because the panels are rigid, they can be used either against the wall or as a freestanding green façade (figure 2.7). Freestanding structures can be used as screens and to isolate views such as fences, columns or beside highways as a noise barrier (figure 2.7). They can also be used to hide mechanical equipment, service areas, storage access and other aspects of a building's system requirements that detract from the aesthetic experience. The panels can be joined and stacked to cover large surfaces, or to cover different formed shapes and curves, are made from recycled content steel and are recycle-able (green roofs, 2008).

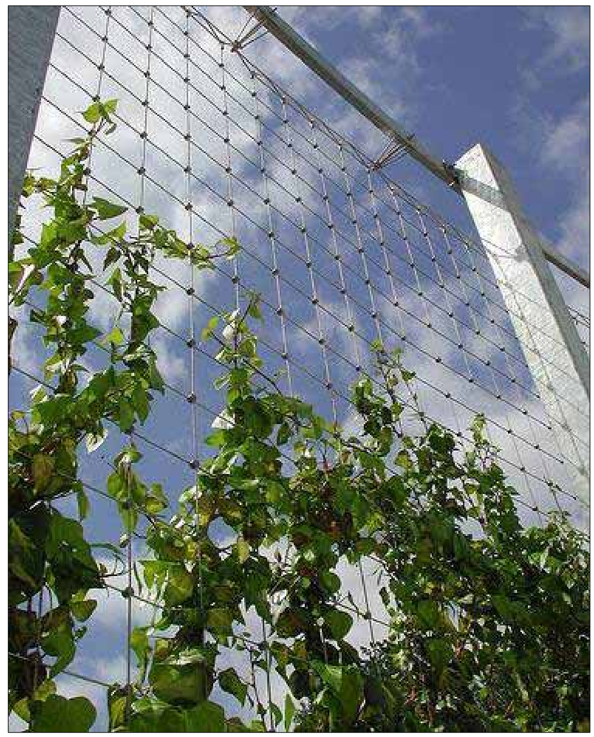



Figure 2.7: freestanding structures as green façades (source: right, www.greenscreen.com; left, www.flickr.com).

Figure 2.8: (a) mounting supporting structure on the Wall (source: www.greenscreen.com); (b) applying green on supporting structure (netting system).

Cable and wire-rope net systems

The cable and wire-rope net systems use either cables and/or a wire-net. Cables are employed on green façades that are designed to support faster growing climbing plants with denser foliage (figures 2.9a and b). Wire-nets are often used to support slower growing plants that need the added support. They are more flexible and provide a greater degree of design applications than cables (figure 2.10). Both systems use high tensile steel cables, anchors and supplementary equipment. Various sizes and patterns can be accommodated as flexible vertical and horizontal wire-ropes are connected through cross clamps.

Figure 2.9: (a) and (b) cable and wire-rope net system (building EGM architecten, Dordrecht).

Figure 2.10: wire-rope net systems (source: carl stahl decorcable innovations).

b) Plants planted in planter boxes

In this case the plants are growing from intermediate planter boxes with soil in it. The planter boxes can be placed at the bottom of façades (figures 2.11a and b) or on rooftops, hanging system (figure 2.12a). A continuous watering system is needed for this system because the plants are not rooted directly in the ground. This system needs also a long covering time of the façade. The covering time depends in this case mainly to the surface of the wall and the amount of plants and the distance between the plants. Due to the small space available in planter boxes, roots of plants cannot grow unlimited. For this reason plants grow to a limited length and width (figure 2.11c). Therefore it is possible and necessary to place the planter boxes at each floor height to avoid bare spaces on the wall (figures 2.13a and b). In this way plants cover the wall sooner. Again there are two possibilities to cover the façade with this technique, namely; plants directly to the wall and indirectly to the wall (figure 2.11).

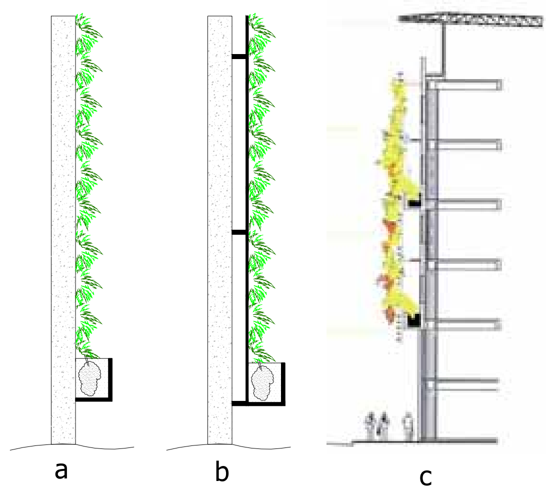


Figure 2.11: the principle of plants from an intermediate planter box; (a) directly to the wall and (b) indirectly to the wall; (c) plants from an intermediate planter box at the bottom of each level, indirectly to the wall (source: www.greenscreen.com).

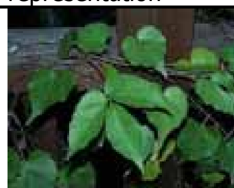
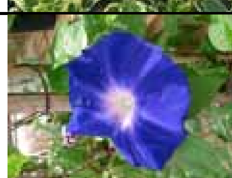
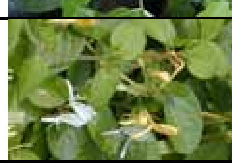
Figure 2.12: plants from intermediate planter boxes with supporting structure; (a) a hotel building (hanging system) (source: www.wallflore.eu); (b) a multi-level parking structure (source: www.greenscreen.com).

Figure 2.13: plants from intermediate planter boxes with supporting structure; (a) a multi-level building in Rotterdam; (b) a multi-level hotel building in Monaco; (source: www.greenwavesystems.eu/verticaletuinen).

Plants suitable for green façades

Table 2.1 shows a list of some plants which are the most common and suitable to use for making green façades.

Table 2.1: plants suitable to make green façade (Yu-Peng yeh, 2010; www.monrovia.com)

name	representation	characteristics	evergreen/ deciduous
Parthenocissus heterophylla		grow fast, good at climbing, suitable for greening areas	evergreen
Campsis grandiflora		easy to propagate ,bloom, look beautiful	deciduous
Rachelospermum jasminoides		bloom, flowers smell fragrant, can be used as herbs	evergreen
Euonymus fortunei		look beautiful, can be used as herbs	evergreen/ deciduous
Ipomoea nil		bloom, look beautiful, can be used as herbs	deciduous
pomoea quamoclit		bloom, look beautiful, can be used as herbs	evergreen
Wisteria sinensis		bloom, look beautiful, can be used as herbs	deciduous
Hedera helix		good at climbing, look beautiful	evergreen
Lonicera japonica		bloom look beautiful, can be used as herbs	deciduous

2.2.2 Wall vegetation

Considering vertical division, walls usually consist of three different zones: the base, the vertical wall surface with joints (fissures) and the top. Wall vegetation is a special type of vertical green, which is usually growing at the surface walls and especially in joints or cracks. This spontaneous growing of plants is a natural process. It has therefore an irregular growing structure on the surface of the wall. Wall vegetation can nowadays be divided into two categories and is shown schematically in figure 2.14.

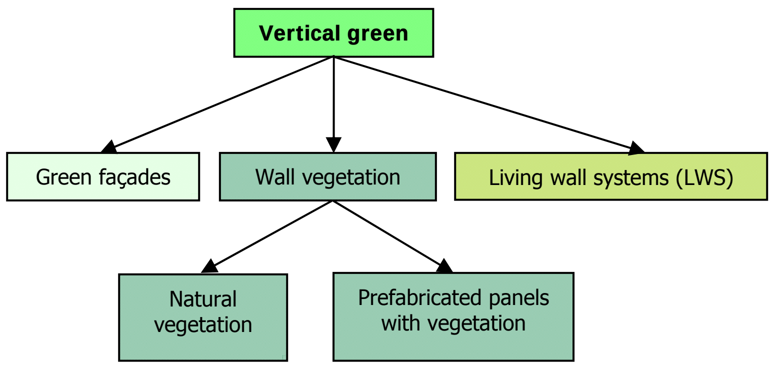


Figure 2.14: diagram of vertical greening systems.

Categories:

a) naturally grown vegetation.
b) concrete (prefabricated) panels with vegetation.

a) Naturally grown vegetation
This type of vertical green can be often found on old walls, monuments, buildings in historical town centre's, disintegrating castle fortifications, shady walls in gardens, etc. Development of plant communities mostly depends on the level of disintegration of mortar, concrete or any other type of binding material. It has an irregular structure and it is growing naturally and without any human intervention (Figure 2.15a, b, c, d and e).

Figure 2.15: (a) the principle of wall vegetation, (b) and (c) naturally wall vegetations.

Figure 2.15: (d) and (e) naturally wall vegetations (source: stadsmuur sienna).

b) Concrete panels with vegetations

This type of vertical green, with concrete panels, is a new development to green structures. Presently there are studies in process to make and test some concrete panels with vegetation on it. These panels are concrete panels with large pores between the used granulates (figure 2.16). The pores are filled with soil to create a growing possibility for plants. The panels are designed with the purpose to take water from natural sources such as rain and snow. By placing the panels with a small angel to the vertical, they can absorb more water, which contributes positively to the growing process. There is a limited number of plant species which can grow and live on concrete or paved surfaces. This related to the high pH value of concrete (pH=13) and water availability.

Figure 2.16: concrete panels (Growcrete) with plants (source: Ottelé, 2010).

2.2.3 Living wall systems (LWS)

Living wall systems are another type of vertical greening. Living wall systems are distinct from green façades in that they support vegetation that is rooted in substrate attached the wall itself, rather than being rooted at the base of the wall, and as a consequence have been likened more to vertical living systems (Dunnett and Kingsbury, 2008; Köhler, 2008). Living wall systems, also called "Mur vegetal", can be built almost everywhere and in different sizes. Living wall systems can perform in various climates, such as in full sunny, shade and can be used in both tropical and temperate climates (Yu-Peng yeh, 2010). Characteristic for living wall systems are the artificial substrates used to let grow vegetation at grade. The walls of buildings are most suited to living wall systems that use hydroponic technology to support plants that are kept physically separate from the wall, for example a drip-feed irrigation system that keeps moist a growing medium placed on the wall but kept separate from the construction material by a waterproof membrane (Dunnett and Kingsbury, 2008), and thereby maintains the integrity of the wall structure. Köhler (2008) notes that living wall systems do not rely on a limited range of climbing flora to the same extent as green façades, and allow a far greater range of species to be planted on the wall surface; this increases the potential for utilising living walls for reconciliation, as species may be planted to address specific functions that may be missing in the urban environment (Francis et al., 2011). Due to the diversity and density of plant life, living wall systems require more intensive maintenance (regular water, nutrients, fertilizer) than green façades (which are rooted into the soil). Living wall systems may also use the wall structure, though they are built out of connecting pre-vegetated panels or integrated fabric systems which can be attached to a (free) standing wall. Living wall systems are not only applied outdoors at façades and civil engineering structures, it can also be used for interior applications in buildings (figure 2.17a, b and c).

Figure 2.17: (a) living wall system inside a building (source: www.Jetsongreen.com); (b) living wall system outdoor (source: www.hyperexperience.com); (c) living wall system on a bridge (source: *www.landscapeinvocation.blogspot.com*).

Living wall systems can be divided into two categories. A distinction can be made between prefabricated living wall systems and insitu living wall systems (figure 2.18).

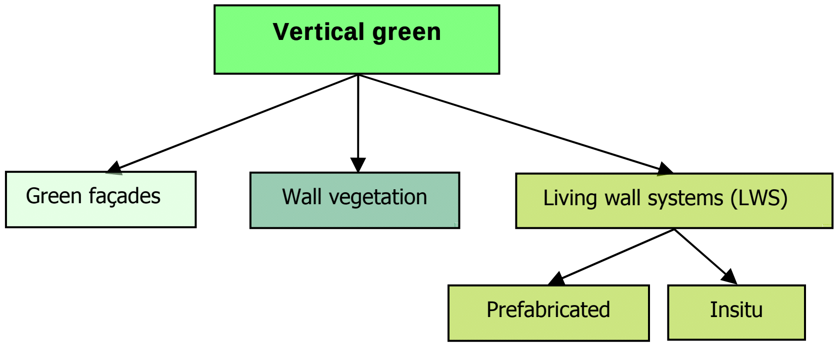


Figure 2.18: diagram of vertical greening systems.

Categories:

a) prefabricated living wall systems.
b) insitu living wall systems.

a) Prefabricated living wall systems

Prefabricated living walls are composed of pre-vegetated panels or integrated fabric systems that are affixed to a structural wall or frame. Modular panels can be comprised of polypropylene plastic containers, geotextiles, irrigation, growing medium and vegetation (figure 2.19). This type of living wall system supports a great diversity of plant species, including a mixture of groundcovers, ferns, low shrubs, perennial flowers, and edible plants.

Figure 2.19: left; living wall system inside a building (source: Middelie, 2009), right; living wall system applied outdoor (source: Middelie, 2009).

The structuring panels in living walls are designed to allow a water flow internally from module to module within each panel, and subsequently from panel to panel. It's common for a drip irrigation line to be installed early on to provide the easiest and most effective method of watering (drainage) possibility. This consists of a drip pipe that is often incorporated into the system. The drip pipe is connected to a water pump that provides the possibility for additional nutrients in to the water system. Nutrients are primarily distributed through an irrigation system that cycles water from the top of the system down. Therefore, researchers developed a special, self-automated watering and nutrition system, to make maintenance of the living wall systems easier (figure 2.20). It is even possible that the responsible office log on to the system and see if the living wall system needs more or less water and whether the amount of nutrients is sufficient.

The use of drinking water for living wall systems is always possible, and the use of collected rain water is depending to polluting substances and spores. Rainwater should be filtered, and needs more maintenance. Because of the pump system, storage area of rain water and maintenance it is not a sustainable choice in the designing process. In a project with multiple façades there are several irrigation systems needed. Every wall has required its own adjustment. It is important to mention that a south orientated wall needs more water than a north orientated façade related to evapotranspiration.
The climatological circumstances play also an important role for water consumption.

Figure 2.20: self-automated watering and nutrition system for living wall systems at Ford building in Amsterdam (source: Middelie, 2009).

Below there is a short list of some prefabricated living wall systems which are available at the moment in the Netherlands (figure 2.21). The systems are chosen on the characteristic properties of the used substrates and they will be briefly described separately.

- Greenwavesystem (planter boxes system)
- Fytowall-Fytogreen (foam based system)
- Wallflore (mineral wool based system)

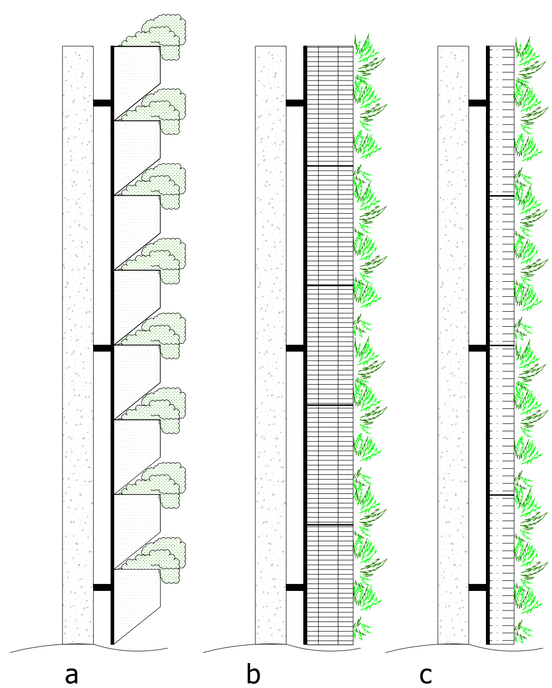


Figure 2.21: (a), (b) and (c) the principles of living wall systems as listed above.

Greenwavesystem
The planter boxes system is developed by Greenwavesystems (figure 2.22). The living wall system consists of indestructible modules made of fibreglass reinforced recyclable HDPE plastic (figure 2.23a en b). These modules are available in three standard colours, and filled

with soil (figure 2.23c). The soil in the boxes makes it possible to plant every conceivable combination of plant species. The boxes have enough depth to plant also bigger plants with larger roots (figure 2.23c). Every module is 600 mm wide, 515 mm high and 200 mm deep. The weight of the system per module without plants is between 25 and 40 kg and depending on the soil mixture. The planter boxes are not only suitable for outdoor but can also be used indoor (inside buildings).

Figure 2.22: left, planter boxes with various plants in it (side view); right, living wall system with planter boxes including various plants.

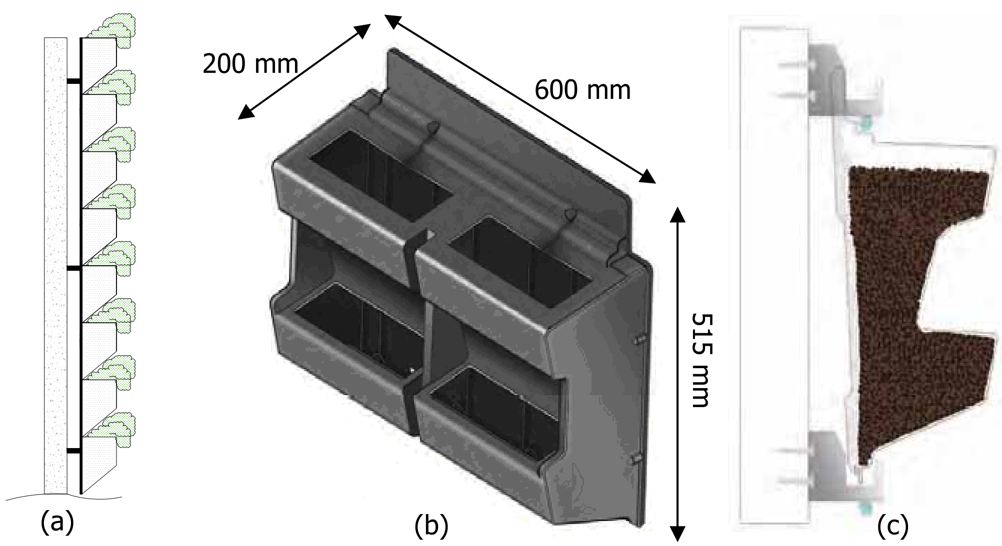


Figure 2.23: (a) principle of planter boxes, (b) module of planter boxes and (c) the section of a planter box with soil in it (source: www.greenwavesystems.eu).

The modules are hanging on a U-profile and there is cavity at the backside. This system covers the façade completely and creates a watertight living wall system. Because of the horizontal implantation the system can also take the sunshine and the rainwater in case of outdoor installation in the natural way. The irrigation pipes run along above the double boxes, which can provide sufficient water for each module (figure 2.24a, b and c).

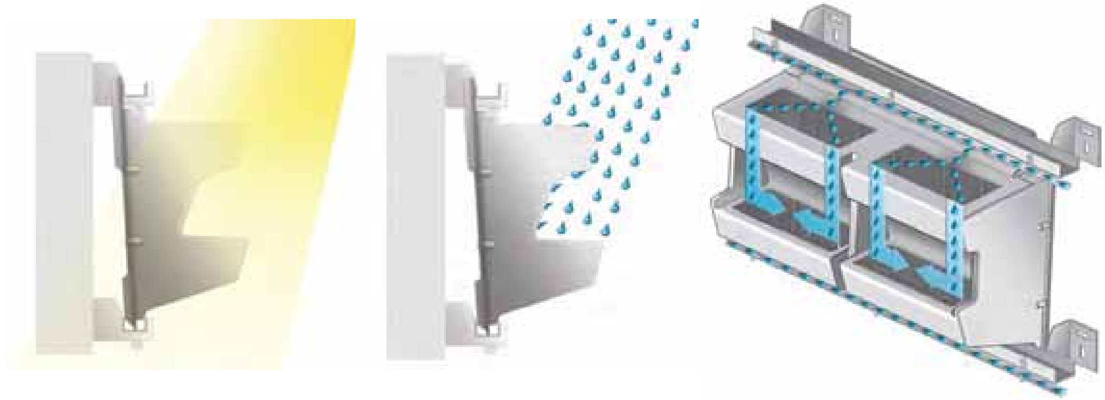
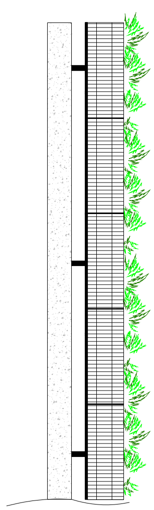


Figure 2.24: (a) sunshine (optimum light collection) on planter boxes (b) rain (optimum water collection) on planter boxes and (c) irrigation system of planter boxes (source: www. greenwavesystem.eu).

Fytowall-Fytogreen

The Fytogreen company produces different greening systems. One of the systems is Fytowall (foam based living wall system), which is a part of the 'Vertical Garden Company' of Fytogreen. The foam based substrate is made of aminoplast resin foam. This results in a light, but very stable and firm white spongy pH neutralised growing media. This media is very water efficient and robust for a wide range of plants and climate types. The system has an easy-to-use inbuilt irrigation system that automatically waters the plants on a drip system by feeding water and fertilizer cross the wall from the above. This system can be applied in both outdoor and indoor situations (figure 2.25a, b and c).



(a)

Figure 2.25: (a) principle of fytowall-fytogreen; (b) forecourt of Marriott Hotel in 'Sydney Hyde Park', curved facade with a selection of grasses and indoor plants and ferns; (c) fytowall system for outside applications (source: www.fytowall.com).

The growing medium is placed in steel baskets (figure 2.26a) and the steel baskets are hooked on an aluminium carrier (figure 2.26b). The aluminium carrier of the system creates a cavity of 50 mm at the backside with the wall. The aluminium styles have a standard distance of 510 mm from each other. The panels of this system have the standard size of 1000 mm x 490 mm x 140 mm and the weight of a panel is about 88 kg/m^2 without plants, by maximum water saturating (figure 2.27).

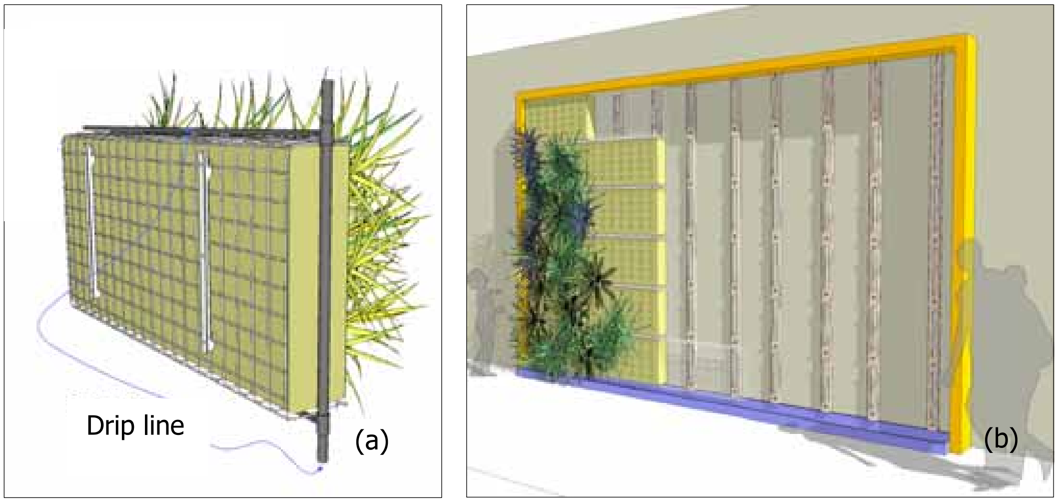


Figure 2.26: (a) steel basket with growing medium in it; (b) aluminium carrier structure for fytowall-fytogreen system (source: www.fytowall.com).

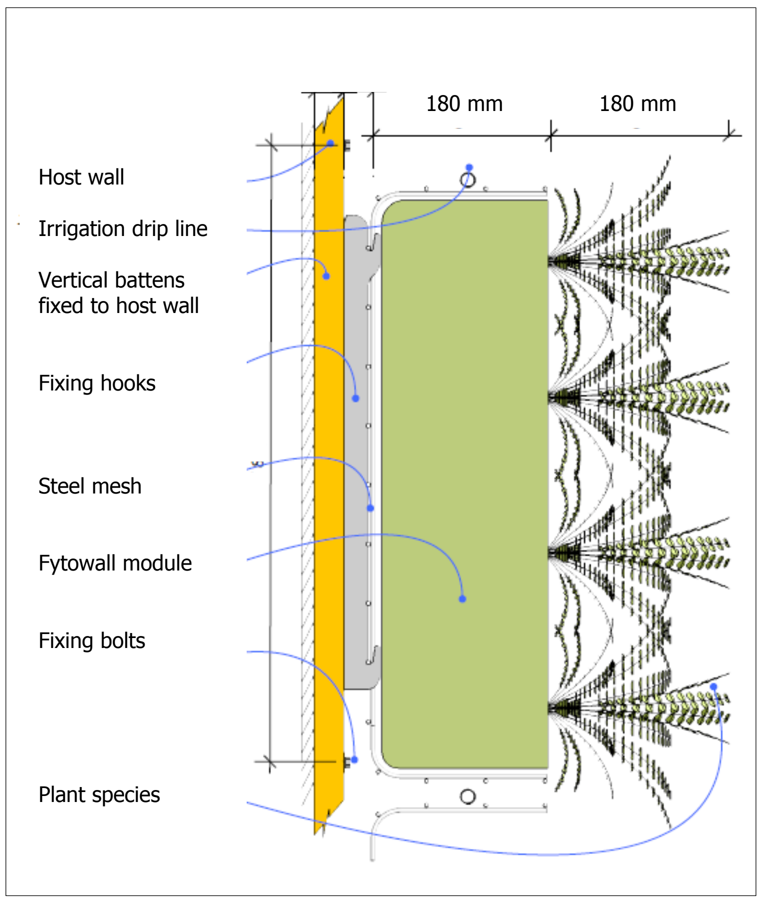
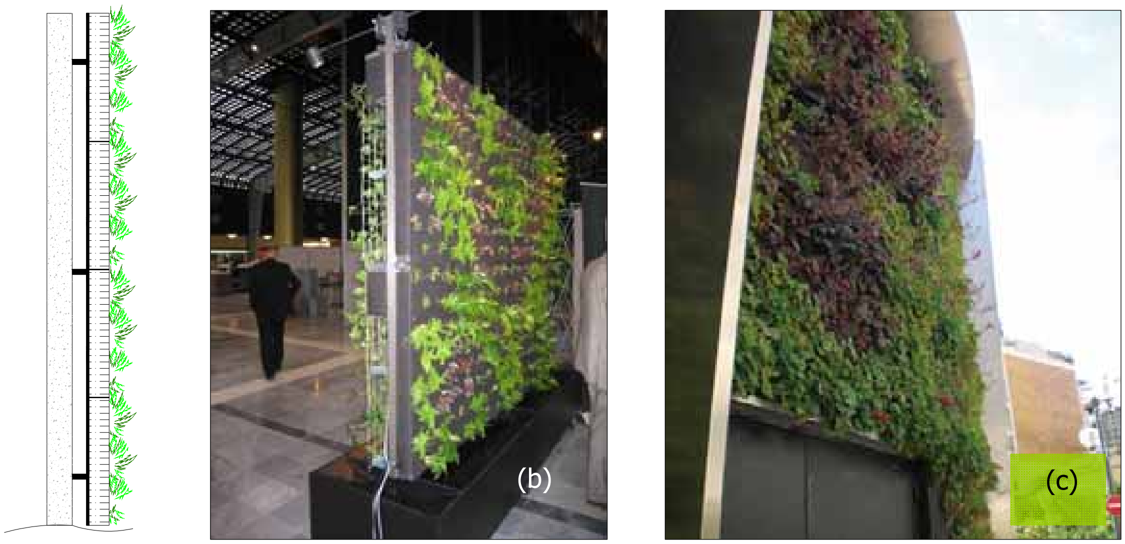


Figure 2.27: vertical detail fytowall-fytogreen system (source: www.fytowall.com).

Wallflore system

This system is made by the company Cultilene in partnership with Saint-Gobain. This living wall system is already applied in different buildings in Europe. There are special designed possibilities for applying different plant species, so that it can be used for different purposes (figure 2.28a, b and c).



(a)

Figure 2.28: (a) principle of mineral wool based living wall system (wallflore); (b) mobile panel wallflore living wall system (source: www.wallflore.eu); (c) wallflore living wall system applied outdoor.

The growing medium used is mineral wool (stone wool, 80 kg/m^3) and the basis of all the living walls of the system consist of an aluminium Fix-lide system. The panels are 75 x 600 x 1000 mm and each panel weight 12 up to 15 kg without plants (figure 2.29). Each panel can contain 16 plants (27 plants/m^2). A dark gray non woven felt made of PP and PE functions as an envelope around the panels (figure 2.30). All the components that can come into contact with salts (from plant nutrition and plant acids) are manufactured from a high quality aluminium alloy (figure 2.31). Furthermore, the system has a complete irrigation network to which the plants water and nutrients are administered. This irrigation network can either work stand alone or as a web-based controlled.

Figure 2.29: aluminium Fix-lide system for wallflore panels (source: wallflore company).

This system can also be used as a hanging system (figure 2.30), with or without additional supporting structure (figure 2.32a and b). The hanging system can be used for example as a screen for balconies or parking garages (figure 2.32c and d).

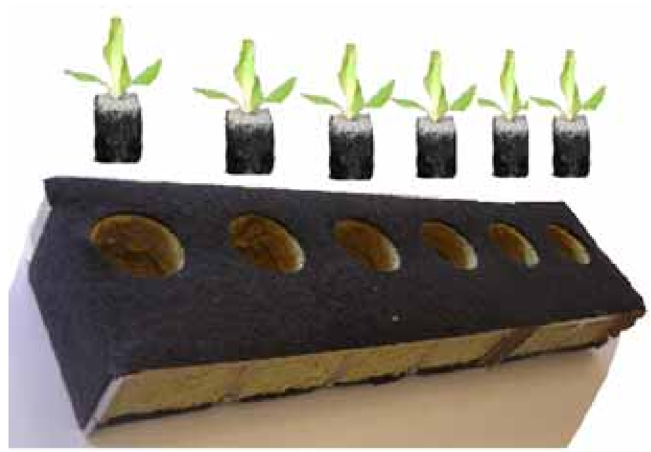


Figure 2.30: wallflore panel with growing medium (Rockwool) and dark gray felt around it. These panels can be used for parking garages for hanging applications.

Figure 2.31: manufactured aluminium alloy with growing medium and a dark gray felt (source: www.wallflore.eu).

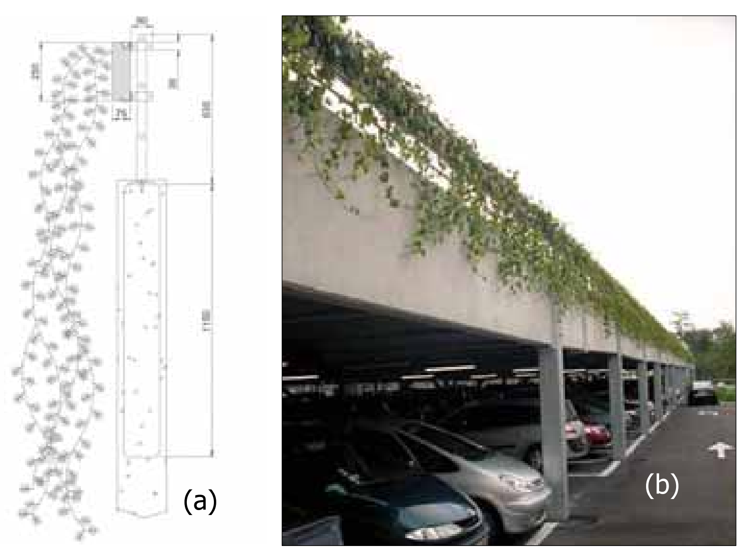


Figure 2.32: (a) hanging system application in a car parking; (b) detail hanging system (source: www.wallflore.eu).

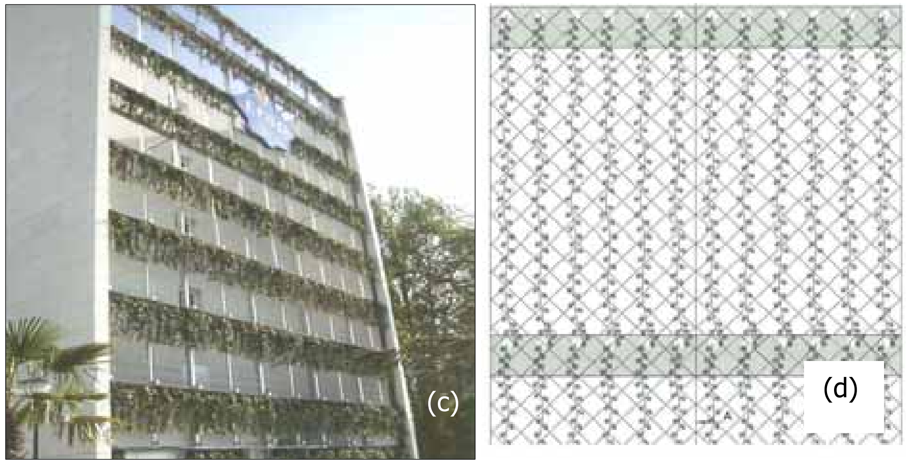


Figure 2.32: (c) hanging system application in a hotel building balconies with supporting structure; (d) detail hanging system with supporting structure (source: www.wallflore.eu).

b) In situ living wall systems

In situ living walls are actually half prepared systems, which can be installed at façades. After installing the felt layers the plants can be placed in the created pockets. The felt layer based system (Wonderwall of Copijn, Patrick Blanc) is one of the in situ living wall systems, which are already applied at different buildings. Figure 2.33 shows the application of felt layers system, which is carried out with different plant species.

Figure 2.33: left, the principle of felt layers system; right, felt layers system in practice ("Black box", Stylos pavilion, Faculty of architecture TUDelft) (source: Geus, 2007).

This system is composed of different felt layers (three layers of textile and a growing felt) with pockets on a PVC plate (figure 2.34a). All these components together are mostly fixed on a steel frame that physically supports plants and growing media. The plants are put into the pockets after that the system is hanged against the façade (figure 2.34b). Also 'Le Mur Vegetal' of the famous French botanist and landscape architect Patrick Blanc is a felt layer based system with created pockets for plants.

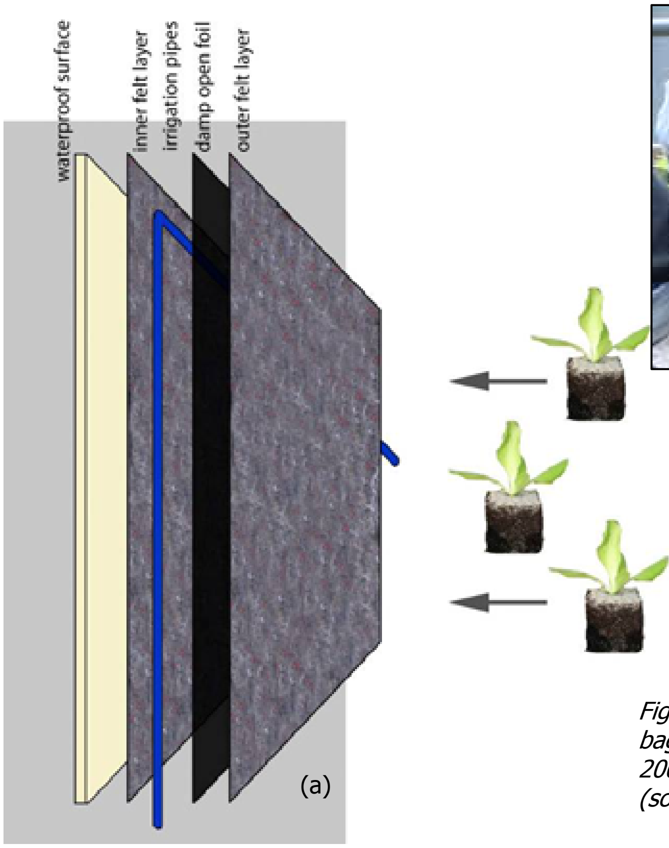


Figure 2.34: (a) the principle of planting in bags by felt layer system (source: Geus, 2007); (b) putting of the plants in bags (source: http://bk.tudelft.nl).

The plants are growing into plant pockets which are always irrigated (figure 2.35). The plants cannot grow indefinitely because of the limited pocket space; it is therefore not possible to apply plants with large tick roots. A continuous watering system is needed, which is functioning automatically and controlled with moisture sensors. The system needs about three litres water per m^2 per day but this depends on the season, weather conditions and on local climatological conditions and orientation of the façade. The overflowing water comes into a leakage profile mounted under the panels. Every squire meter consists out of 25 plants. The weight of the system inclusive the steel frame is about 100 kg/m^2.

Figure 2.35: (a) plant bag from a façade of Mercator sport plaza (Amsterdam); (b) the building of Mercator sport plaza covered with LWS based on felt layers (source: www.deGroenestad.nl).

Plants suitable for living wall systems

Table 2.2 shows a list of some plants which are the most common and suitable to use for making living walls.

Table 2.2: plants suitable to make living walls (Yu-Peng yeh, 2010; www.monrovia.com; www.livingwallart.com)

name	representation	characteristics	evergreen/deciduous	outdoor/indoor
Philodendron scandens		bloom, look beautiful, easy-to-grow plant, grows also in shade	evergreen	outdoor and indoor
Dracaena		bloom early summer to late summer, low maintenance	evergreen	outdoor in summer and indoor in all seasons
English ivy		grow fast, good at climbing, suitable for greening areas	evergreen	outdoor
Spider plant		easy to propagate ,bloom, look beautiful	evergreen	outdoor and indoor
Golden pothos		bloom, look beautiful, can be used as herbs	semi evergreen	outdoor and indoor
Peace lily		white bloom, look beautiful, can be used as herbs	evergreen	indoor
Chinese evergreen		low growing, durable plant, look beautiful	evergreen	outdoor

2.3 Comparative assessment of vertical greening systems

After a description of each system according to the diagram in figure 1.2, it is needed to make an overview of all vertical greening system with their characteristics compared to each other (table 2.3). Table 2.3 will be used to make an assessment between the different systems and to consider which systems are preferred and necessary to be worked out further in this report. The advantages and disadvantages of the vertical greening systems are described in next chapter.

The diagram in figure 2.36 shows three main categories and totally ten sub classifications of vertical greening systems based on literature (Köhler, 1993; Hermy et al., 2005; Ottelé, 2011; Krusche et al., 1982). The thick arrows with coloured boxes show the vertical greening principles which are measured in a special designed climate chamber (subject of chapter 4 and 5) as a further elaboration of PhD research (Ottelé, 2011).

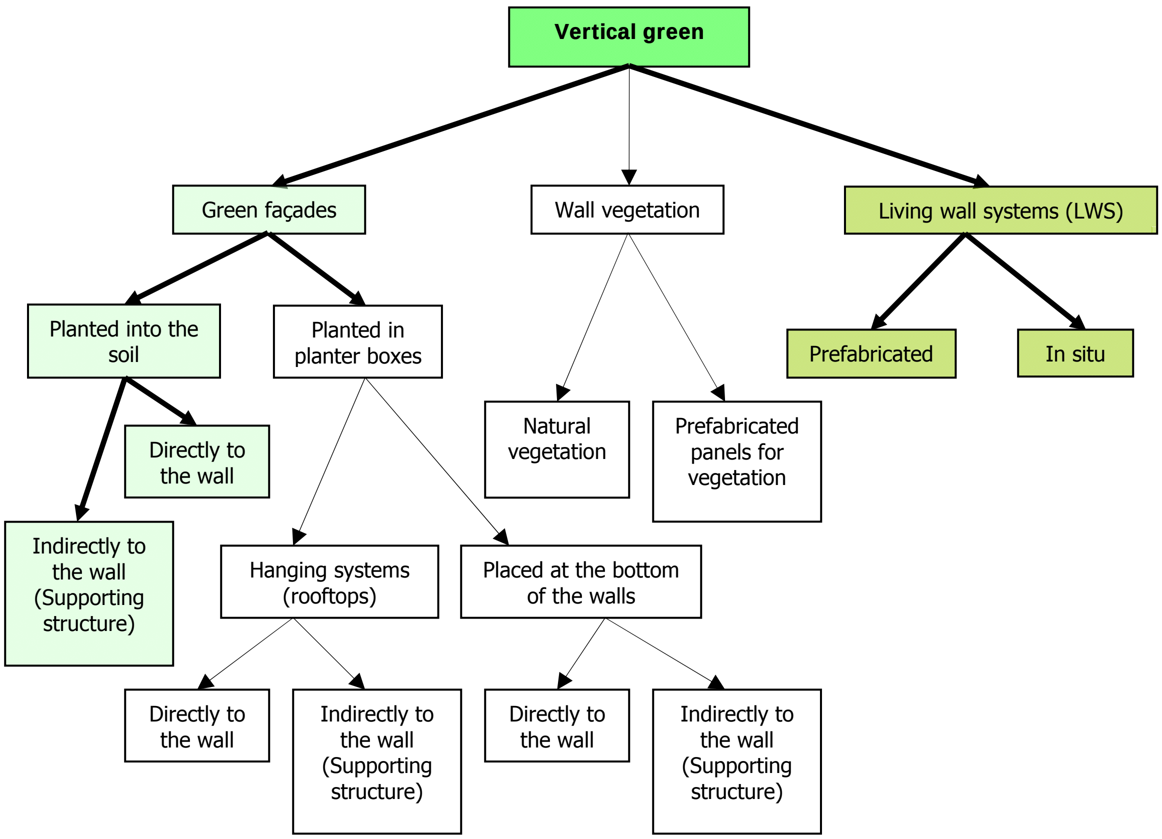
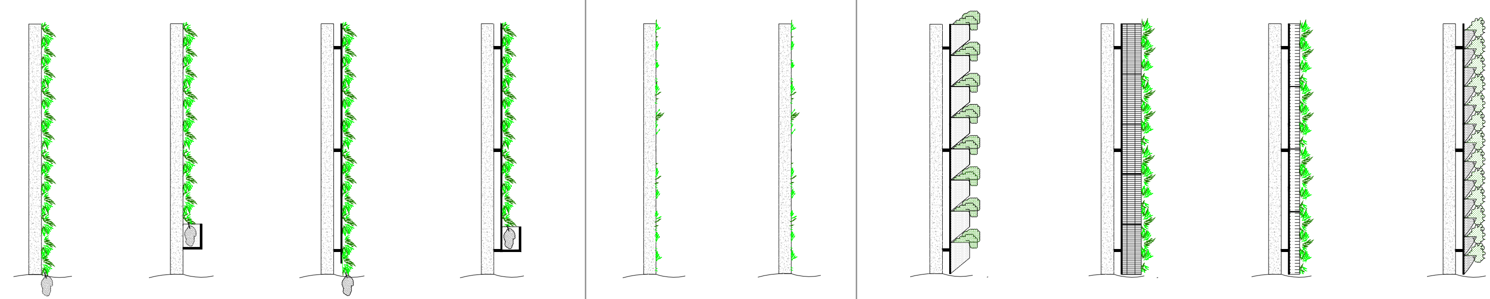


Figure 2.36: diagram of vertical greening systems based on literature (Krusche et al., 1982; Köhler, 1993; Hermy et al., 2005; Ottelé, 2011), comparative assessment.

Table 2.3: overview of all vertical greening system with their characteristics.

Vertical green type	**green façade**				**wall vegetation**		**living wall system (LWS)**			
type	direct*	direct	indirect*	indirect	natural	concrete panel	planter boxes*	foam based*	mineral wool based*	felt layers*
Schematic representation / **System properties**										
rooting space	in the ground	planter box	in the ground	planter box	wall	panel	planter boxes	box	plate	pockets
substrate	soil	soil	soil	soil	façade material	soil	soil	aminoplast	rock wool	felt
supporting system	--	--	for plants	for plants	--	for module	for module	for module	for module	for module
plant specie	climbing plant	climbing plant	climbing plant	climbing plant	shrubs	small shrubs	shrubs	shrubs	shrubs	shrubs
air cavity (mm)	0	0	3000≥50	3000≥ ≥50	0	0	≈50	≈50	≈50	≈50
total thickness greening system (mm)	200	200	100	100	≤300	≤350	≤450	≤500	≤400	≤350
maximum greening height (m)	30	30	30	30	depending to plant specie	unlimited	unlimited	unlimited	unlimited	unlimited
plants	$\leq 4/m^1$	$\leq 4/m^1$	$\leq 4/m^1$	$\leq 4/m^1$	--	<10	$30/m^2$	$22\text{-}25/m^2$	$27/m^2$	$25/m^2$
system weight kg/m^2	>5.5	>5.5	>4.3	>4.3	--	>300	>150	100-120	40-60	100
natural rainwater/irrigation system	natural rainwater	irrigation system	natural rainwater	irrigation system	natural rainwater	natural rainwater	irrigation system	irrigation system	irrigation system	irrigation system
plant life expectation (Y)	50	50	50	50	≈100	50	10	3.5	3.5	3.5
biodegradable	yes	yes	plant-yes	plant-yes	plant-yes	plant-yes	plant-yes	foam and plant-yes	plant-yes	plant-yes
maintenance	pruning	pruning	pruning	pruning	--	pruning	replacement/pruning	replacement/pruning	replacement/pruning	replacement/pruning
realization time (Y)	≈30	≈2-3	≈30	≈2-3	--	≈1	<1	<1	<1	<1
price (€/m²)	30-45	≈200	40-75	100-800	--	--	400-600	750-1200	500-750	350-750
prefabricated/in situ	insitu	prefabricated/in situ	insitu	prefabricated/insitu	insitu	prefabricated	prefabricated	prefabricated	prefabricated	prefabricated/insitu

* measured in experimental set up (hotbox).

2.3.1 Measured vertical greening systems

The vertical greening systems that are measured and examined more deeply inside this report are based on figure 2.36 and table 2.3. The schematisation or greening principles of vertical greening systems are shown in figure 2.37.

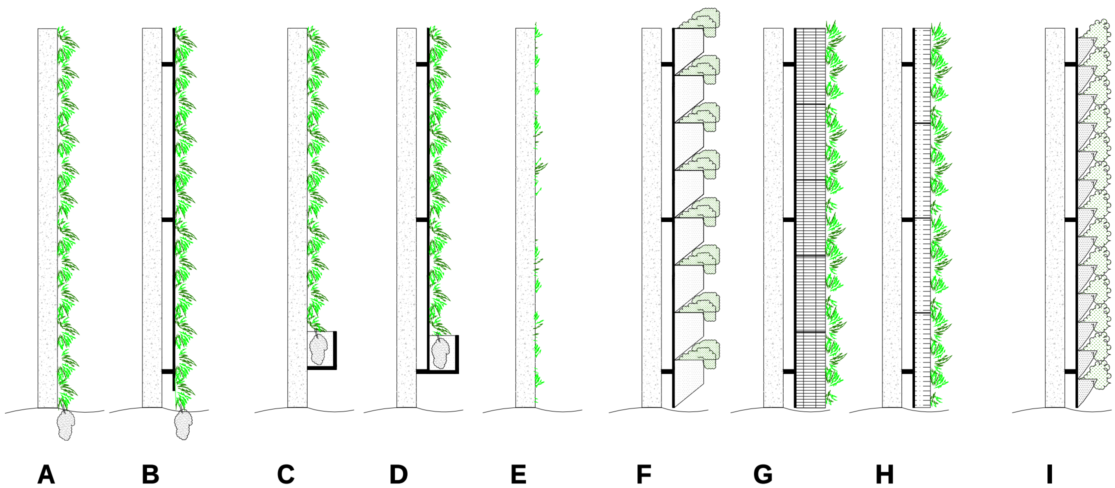


Figure 2.37: schematisation of the vertical greening systems (source: Ottelé, 2011).

A. *Hedera helix*, directly, planted in to the ground
B. *Hedera helix*, indirectly, planted in to the ground
C. *Hedera helix*, directly, planted in a planter box
D. *Hedera helix*, indirectly, planted in a planter box
E. wall vegetation
F. planter box system (LWS)
G. foam based system (LWS)
H. mineral wool based system (LWS)
I. felt layers system (LWS)

A bare wall and six of the total ten vertical greening systems from table 2.3 are measured in the designed test set up (hotbox) and are listed below. The six measured vertical greening systems are based on Ottelé (2011).

Green façades

1) *Hedera helix*, directly to the wall (figure 2.37A)
2) *Hedera helix*, indirectly to the wall (figure 2.37B)

Living wall systems (LWS)

3) planter boxes system (figure 2.37F)
4) foam based system (figure 2.37G)
5) mineral wool based system (figure 2.37H)
6) felt layers system (figure 2.37I)

Due to similar properties of the vertical greening systems, a well thought-out choice has to be taken which systems will be examined. As became clear from literature included (summarized) in

table 2.3 green façades are fundamentally different compared to wall vegetation and living wall systems. The beneficial claims for all of the noted systems are more or less the same (no distinction is made). Ottelé, (2011) is the first researcher who reported about differences between greening systems according to their growing principle (greened directly, LWS with different substrates, etc.).
To investigate the influences of vertical greening on a building structure, it is needed to compare the vertical greening systems with a non greened (bare) façade related to moisture transport, condensation, etc. Since the study aimed to investigate a possible influence of vertical green at the building level, wall vegetation (figure 2.37E) is left aside, because of the less vegetation available on the system itself. Green façades and living wall systems are the two major categories which are fundamentally different and the study will focus on these two.

Because of the differences (air cavity, supporting structure and growing substrate) between a direct an indirect greening system and the possible influence on the thermal moisture behaviour of a structure, both of the principles (figure 2.37A and B) will be examined further in this report. Living wall systems can be divided according to their growing substrate. Ottelé (2011) distinguish planter boxes (filled with soil), foam, mineral wool and felt layers based systems (figure 2.37F-I). It can be expected that each of these individual systems can have their own specific properties and material usage, but they have also a lot of similarities such as air cavity, supporting system, irrigation system and etc. (table 2.3).

For the moisture transport calculations (chapter 5) a direct and an indirect greening system will be analyzed. It is important to know if moisture transport can take place with applying of the mentioned greening systems because there is a lot mentioned in the relevant literature about these two systems. It is also important to note if an air cavity (in case of indirect greening) influences the moisture transport through a wall compared to direct greening on façade. Beside this, a living wall system will be examined on the moisture transport, since this type of vertical greening is completely different than the traditional green façade and this kind of measurements for living wall systems is not taken place yet. This gives also an additional value for applying living wall systems. Due to similarities of living wall systems only one living wall system (based on planter boxes, figure 2.37F) will be examined for comparing with a bare wall and to look if the influences are different than the other measured vertical greening systems.

Chapter 6 discusses a life cycle analysis regarding vertical greening systems. Four of the six measured vertical greening systems (direct greening system, indirect greening system, LWS based on planter boxes and a LWS based on felt layers) are already studied by Ottelé et al. (2011). Since LWS based on mineral wool (figure 2.37H) and LWS base on foam (figure 2.37I) are made from different materials and they have different substrates they will be both discussed in chapter 6.

3 Advantages and disadvantages of vertical greening

3.1 Introduction

This chapter deals with the advantages and disadvantages of vertical greening systems which are applicable in practice. Before applying vertical greening it is important to know what are the advantages and disadvantages according to scientific research and how people experience green façades now and in the past. Living wall systems is a relative new application form of vertical greening technology, which can have its own added advantages and disadvantages to the subject of vertical green.

3.1.1 Functional aspects

About the use of vertical greening there are still prejudices, although this has little or no hard scientific evidence (Brandwein, 1998). There are some advantages and disadvantages or problems that vertical green can create. People experience the functional aspects of vertical greening more as an advantage than a disadvantage. According to Löschmann (2001) there is not hard scientific evidence for disadvantages that people mention. Table 3.1 shows the results of a survey by 6000 people who lives in a building with vertical green on it in Köln, Germany.

Table 3.1: advantages and disadvantages of vertical greening systems according to Hermy et al., 2005 and Löschmann, 2001.

Advantages	**Disadvantages**
a beautiful street view	prune frequently
more green in the city	leaf fall and leaf cleanup
better healthiness	difficult with to renovate the façade
aesthetics value	clogged gutters and drains
habitat for birds	room darkness
enjoying the nature	wall damage
cooling in the summer	increasing insects
environmentally friendly	(extra) costs
better air quality	lice and more dirt inside house
better building character	sewer damage by roots

Ignorance of citizen and architect and erroneous information can cause this kind of rumours (Löschmann, 2001). The problem can come from three sides: the building, the plants and humans.

- building (cracks in façade, façade material, bearing structure, etc).
- plants (type of plants, foliage thickness, plant age, etc).
- human (pruning, watering, etc).

3.2 Advantages of vertical greening

As literature studies into vertical greening show, there are many advantages and claims. Vertical greening systems are able to:

1) filter air particulates to improve air quality (Pope et al., 2009).
2) reduce the urban heat island effect (Yu-Peng yeh, 2010).
3) provide sound insulation (Wong et al., 2010).

4) moderate a building's internal temperature via external shading (Akbari et al. 1997; Hermy, 2005; Kumar et al., 2004).
5) create a microclimate, which will help to alter the climate of a city as a whole (Alexandri et al, 2006).
6) provide biodiversity and a natural animal habitat (Oliveira et al., 2010).
7) be very beautiful and can protect the wall against graffiti (Peck et al., 1999).
8) improve the insulation properties in summer and winter (Ottelé, 2011).

Certain advantages from the list above are at the moment under the interest of architects, policy makers and engineers which are frequently discussed about environmentally friendly living areas. The mentioned advantages will be briefly discussed below.

3.2.1 Air quality improvement

Air quality improvements are at the moment mainly related to the adsorption of fine dust particles (Particulate Matter) from the air. At the moment there are several problems with particulate matter (PM_x), due to exceeding the concentration limits given in the standards worldwide (van den Berg et al., 2010). High concentrations of fine dust can lead to health risks such as cardio vascular diseases (Pope et al., 2009). The penetration of particles smaller than PM_{10} through the lung into the circulation can affect the organs such as the heart and ultrafine particles penetrated into the blood, deposited in cardiac tissue, and caused cardiac arrhythmia and death (Oberdorster et al., 1996). In short it means that, the smaller the particles, the more dangerous for human health. To reduce the air pollution especially in population-dense urban areas, the vertical greening on the façades is beneficial than the trees through the streets (figure 3.1). Vertical greening can circulate the pollution from the air better and sooner, this in contrast by the trees that can block the street canyon. The greening benefits resulting from space greening of building walls and bases cannot only improve overall urban environmental quality and air quality, it can also improve the added value of buildings, e.g. increasing asset value, improving image and reputation, and increasing market competitive ability (Chang, 2010).

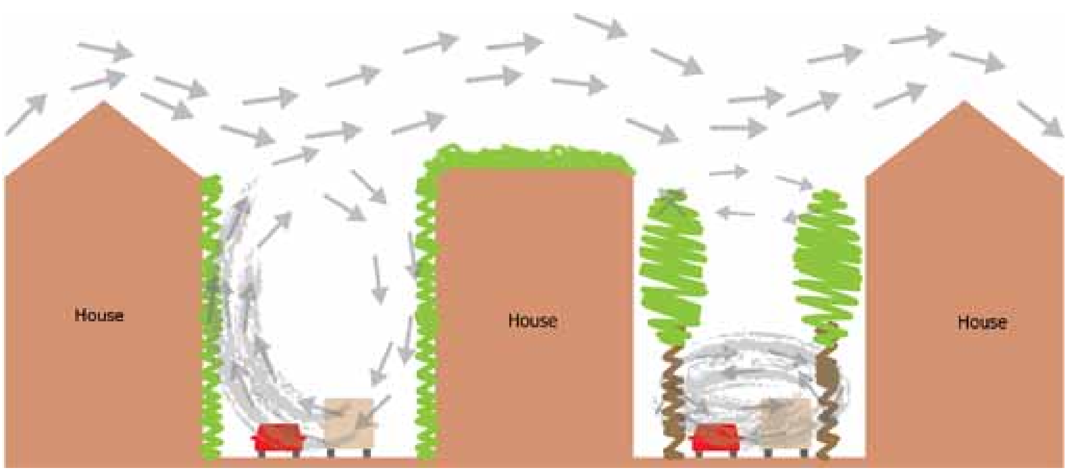


Figure 3.1: air circulation through streets with vertical greening compared to trees (source: Ottelé, 2008).

3.2.2 Urban heat island effect (UHI)

An urban heat island (UHI) is a metropolitan area which is significantly warmer than its surrounding rural area, especially at winter season (figure 3.2). To avoid confusion with global warming, scientists call this phenomenon the "Urban Heat Island Effect". There are several reasons that may explain the heat island effect, but the main reason is the excessive urban development. For instance, in order to construct rooms, large numbers of vegetation spaces have been replaced by concrete and asphalt, which will 'soak up' heat in the daytime and store it. The energy is then released during the night time (Lozadaa et al., 2005). Moreover, heat released from vehicles, air conditioners and places like factories also add to the heat problem. Heated gases are being produced everyday, but there is not enough vegetation to absorb them. Another reason why temperatures in cities tend to be warmer than its surroundings is due to decreased amounts of evaporation. As the water evaporates the process of changing from a liquid to a gas uses latent heat, which cools the surroundings. However, in order to have more lands, pounds and lakes in cities are being filled, leaving cities less water and less evaporation than the countryside. With the concrete and asphalt working as giant storage heaters, vehicles, factories and air conditioners producing heated gases, the serious lack of vegetation and water, the urban heat island effect is getting more and more serious in over-populated cities (Yu-Peng yeh, 2010).

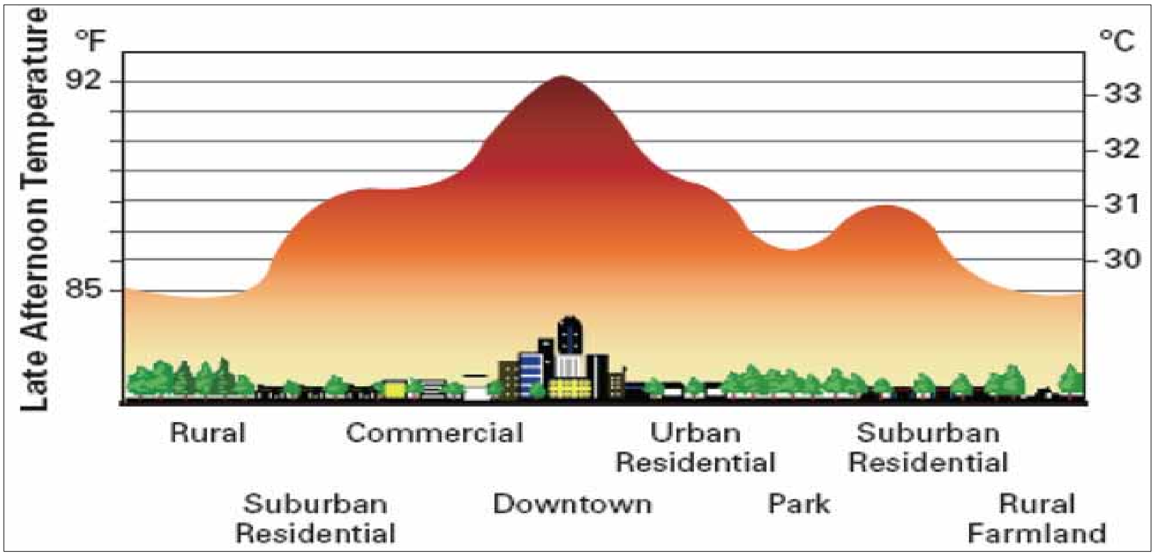


Figure 3.2: an urban heat island is a metropolitan area which is significantly warmer than its surrounding rural areas especially in late afternoons and nights.
(source: http://deadwildroses.files.wordpress.com/2010/06/heat-island.jpg).

The greening of the façade of building walls, or vertical greening systems, has yet to be fully explored and exploited. Simply due to the sheer amount of building walls, the widespread use of vertical greening systems not only represents a great potential in mitigating the UHI effect through evapotranspiration and shading, it is also a highly impactful way of transforming the urban landscape (Wong et al., 2009). It can be also noted that vegetation can alleviate UHI directly by shading heat-absorbing surfaces and through evapotranspiration cooling (McPherson, 1994). Vegetation can dramatically reduce the maximum temperatures of a building by shading walls from the sun, with daily temperature fluctuation being reduced by as much as 50% (Dunnett et al., 2008). Through evapotranspiration, large amounts of solar radiation can be converted into latent heat which does not cause temperature to rise. In addition, a façade fully covered by greenery is protected from intense solar radiation in summer and can reflect or absorb in its leaf cover between 40% and 80% of the received radiation, depending on the amount and type of greenery (Climate booklet for urban development, 2008).

3.2.3 Sound insulation

After several decades of fast urban growth, many big cities are densely overpopulated. The scarcity of land causes many buildings to be constructed very close to expressways or bus terminals, exposing occupants to serious noise pollution. It was found that more than 44% of the population within the European Union was exposed to road traffic noise levels over 55 dB in 2000 (Boer et al., 2007). Cities who are aiming to create a new sustainable urban lifestyle have found that greenery is a key element in addressing this noise pollution (Wong et al., 2009). According to Wong et al., (2009), not all vertical greening systems exhibit a good noise reduction. The most greening systems have a reduction of around 5–10 dB for low to middle frequency range. This acoustics reduction is perceptible or even clearly noticeable for human perception in the change of sound intensity. The growing media in living wall systems will contribute to a reduction of sound levels that transmit through or reflect from the living wall system. Factors that influence noise reduction include the depth of the growing media, the materials used as structural components of the living wall system, and the overall coverage (Cook et al., 1974).

3.2.4 Moderating a building's internal temperature via external shading

The shading and the corresponding reduction of the temperature, is the reason why climbers are commonly used in Mediterranean areas against walls or as a canopy over terraces (Hermy, 2005). Irradiance reductions due to plants can reduce energy use for space cooling, and increase energy use for space heating. Plant canopies that shade buildings move the active heat absorbing surface from the building envelope to leaves (Gregory et al., 1987). Akbari et al. (1997) have described the cooling energy potential of shade trees by reduction of the local ambient temperature. For their biological functions such as photosynthesis, respiration, transpiration and evaporation, the foliage materials absorb a significant proportion of the solar radiation. Thermal protection techniques of green roof can provide a great degree of reduction in the local air temperature near canopy, thus reducing the incoming heat flux into the building (Kumar et al., 2004).

3.2.5 Creating a microclimate

Urban surfaces which are not used, such as the building envelope (walls and roofs), could easily be covered with vegetation and alter the microclimate of the built environment, as well as the local climate of the city. The magnitude of temperature decreases due to this transformation depends on the climatic characteristics, the amount of vegetation and urban geometry (Alexandri et al, 2006). Building thermal performance can be significantly affected by the influence of vegetation on microclimate. Influence on solar irradiance and air flow are probably the most significant and the best documented, although vegetation influences on air temperature, humidity, and long wave radiation exchange may also be significant (Gregory et al., 1987). Vegetation can play an important role in the topoclimate of towns and the microclimate of buildings. With buildings, some vegetative climatic effects could be made by combining green cover on walls, roofs and open spaces in the vicinity of buildings (Wilmers, 1990).

3.2.6 Providing biodiversity and a natural animal habitat

Urbanization creates new challenges for biodiversity conservation. As a large part of the world's population moves from rural to urban areas, there are changes in the link between human activities and biodiversity, and consequently to the way we should think biodiversity conservation policies. However, scarce attention has been given to understand how to make cities more biodiversity friendly, both within the urban fabric, but particularly in faraway places (Oliveira et al., 2010). Biodiversity is considered a key component of ecosystems and as such a key determinant of ecosystem functioning (Watson and Zakri, 2005).

The use of vertical greening systems to support biodiversity is being explored and current research on the abilities of vertical greening systems to provide this benefit is scarce. Large scale vertical greening projects have been created to use indigenous native plant species and create habitat as urban reforestation. The design of vertical greening systems for biodiversity or ecological restoration requires that the designers or their consultants have an intimate knowledge of the requirements of the plants in the region where the project is being implemented, as well as the specific needs of the various fauna (Green roofs, 2008).

3.2.7 Aesthetics and wall protection against graffiti

Vertical greening systems provide aesthetic variation in an environment in which people carry out their daily activities. Numerous studies (Ulrich, 1984; Ulrich, et al., 1991; Peck et al., 1999; Köhler, 1993; Hermy et al., 2005) have linked the presence of plants to improved human health and mental well being. Currently, aesthetic improvements are the primary design objective for most vertical green projects. Large parking structures, campus buildings, urban streets with repetitive façades, public park buildings, transit shelters, retail buildings, all provide an opportunity to design with green walls to create aesthetic improvement. Implementing patterns, rhythms, and shapes and the use of plant textures and the inviting qualities of designing with nature can all contribute to aesthetic improvement (Peck et al., 1999). Another advantage of vertical greening is protection of the façade against graffiti. The large surfaces of the building façades are attractive for graffiti artists, which in not always interesting for the owners and users of the buildings. Figure 3.3 shows how vertical greening can give a beautiful and desirable image to the façades, which can simultaneously protect the façade against graffiti.

Figure 3.3: the façade of a building; left, before applying green and right, after applying green on it. (source :http://pileofphotos.com/pics/287910building_graffiti_01.jpg).

3.2.8 Improving of the insulation property of the building

As it is already mentioned by 3.2.4 the plants can influence the temperature gradient inside and out side the buildings. Not only the shading property is an advantage but also plants have a small contribution to the insulation property of the buildings. In a research project (Stec et al., 2005) aimed to define the thermal performance of a façade covered with plants, a simulation model was developed to analyze the influence of plants on the performance of the façade. Further simulations of the entire building proved that plants can contribute to a comfortable indoor climate and energy savings (Stec et al., 2005).

Plants, especially the living wall systems are protecting the building envelope against the sunshine and freezing weather which is beneficial for the thermal behaviour of the building indoor as well as outdoor. Vertical greening improves the insulation property of the building but the insulation material plays the major role and they are not irreplaceable (Ottelé, 2011). Vertical greening systems improve thermal insulation capacity through external temperature regulation. The extent of the savings depends on various factors such as climate, distance from sides of buildings, building envelope type, and density of plant coverage. This can impact both the cooling and heating (Stec et al., 2005).

3.3 Disadvantages of vertical greening systems

Although there are many benefits in reintroducing vegetation to the surfaces of urban buildings and their related spaces, some technical problems are faced during implementation (Johnston et al., 1993). Living wall systems is relative new technology and rarely investigated yet (Ottelé, 2011). There are no real disadvantages known for living wall systems. Below is a short list of disadvantages which are known during the research.

1) chance of damage on façade in case of green façade directly to the wall (Hermy et al., 2005; Löschmann, 2001; Köhler, 1993).
2) maintenance of vertical greening systems (Köhler, 1993; Yu-Peng yeh, 2010; Ottelé, 2011).
3) costs of vertical green systems, especially living wall systems (Middelie 2009; Ottelé, 2011).
4) irrigation systems (Yu-Peng yeh, 2010; Ottelé, 2011).

3.3.1 Chance damage on façade in case of green façade directly to the wall

The most of damages on the walls can be affected by self climbing's plants such as (*Hedera helix*) ivy plants. The problem can be divided in two groups:

- roots which are penetrating through the foundation and sewerage pipes in case of green façade directly to the wall (Hermy et al., 2005).
- adhesive structures (sucker root structure) of plants directly to the wall (Hermy et al., 2005; Köhler, 1993).

The first problem is less discussed in literature and the main point is actually the second problem (figure 3.4).

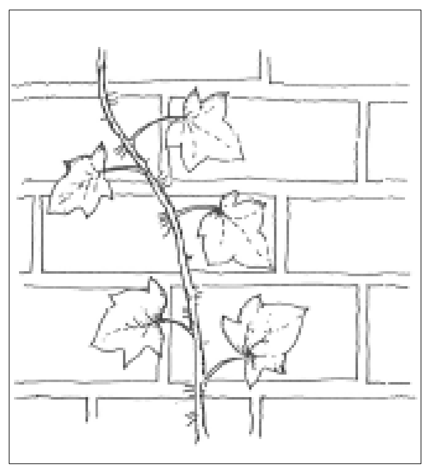


Figure 3.4: sucker root structure of plants (Hedera helix) directly to the wall (source: left, Ottelé, 2011; right, Minke and Witter, 1982).

Actually the adhesive root structure of the plants does not penetrate into the wall. But if there are some small cracks present at the wall, in which the sucker roots can penetrate, it can cause damage. If the wall is very smooth, than the adhesive (sucker) roots would separate organic acids and react with limestone materials and forms crystalline compounds. With this chemical reaction the sucker roots can penetrate a few micrometers inside the wall (Köhler, 1993). It is important to mention that this phenomenon is very low and small which is only visible with a stereomicroscope. This shows that plants with sucker roots can suck the wall very firmly which is actually a good characteristic of these plants for growing on façades.

Because of the thin stems and the footrope character, the plants grow easily to the dark holes and by taking off the plants from the wall, the sucker roots remain on the wall (figure 3.5), which is difficult to remove (Hermy et al., 2005). By taking off the plants also some loose layers from the wall structure can remove, and cause tensions in the wall, which forms the main damage.

Figure 3.5: left, sucker root structure remains after removing the plants (Hedera helix) from the wall; right, biodiversity due to sucker root structures.

3.3.2 Maintenance of vertical greening systems

All vertical greening systems require some degree of maintenance because they are living systems. The amount of maintenance a user is willing to provide is an important design factor that may impact the selection of the type of system and plant species installed.

Green façades

Green façades generally use *Hedera* or/and vines that may grow from ground soil or from planter boxes and each location will have different irrigation and nutrient requirements. Site location and conditions may require that a normally robust or non-dependent vine species be given additional irrigation and nutrients. Some plant species will be deciduous and some provide fruits or flowers in abundance that may require additional care and maintenance. Most plants will benefit from pruning (long-term maintenance) and respond to the care given to landscape elements in general. In case of vertical greening indirect to the wall, Cable and Wire-Rope Systems may require periodic checking of the cable tensions to ensure that the elements are properly in place as the plants mature.

Living wall systems

Due to the diversity and density of plant life, living wall systems typically require more intensive maintenance (e.g. a supply of nutrients to fertilize the plants) than green façades. The degree of maintenance may also be influenced by the user expectations of the aesthetic qualities of a living wall system installation and at what level flourishing vegetation needs to be maintained (Perini et al., 2011). A few maintenance requirements are described below.

- vegetation with high nutrient requirements will generally require a greater degree of care than those that have evolved from nutrient poor environments (Yu-Peng yeh, 2010).
- living wall systems require regular pruning (long-term maintenance) and the precise degree to which maintenance will be required will depend on the type of living wall system and the vegetation used.
- replacement of plant species when they are died, and selecting of the right plant species (figure 3.6a) (Ottelé, 2011).

- replacement of panels by deterioration (figure 3.7b). For some systems e.g. felt layers, it is necessary to change the panels when the felt layers are torn or damaged (Ottelé, 2011).

Figure 3.7: (a) bare parts on a felt layer system with died plants (source: Middelie, 2009); (b) torn pockets, water leakage and degradation of the substrate on a panel of felt layer system (source: Peters, 2011).

- if the plant species are not evergreen, they can die in the winter which is not a beautiful view. Therefore it is important to choose the suitable plant species according to the climate (Köhler, 1993).

Figure 3.8: deterioration of living wall panels, Islington, North-London (source: Middelie, 2009).

3.3.3 Costs of vertical green systems

Construction costs

Vertical greening systems are an expensive cladding technique (Ottelé, 2011). According to Middelie (2009) and Perini et al. (2010) the initial costs to build a vertical greening system based on living wall systems, can be between 350 till 1200 euro per square meter façade. The living wall systems are much more expensive than green façades with climbing plants, because of an irrigation system, more materials involved, more plant species, etc.

Compared to the climbing plants, the living wall systems can fulfil various functions and increase the variety of plants that can be used. The living wall systems have a complex design and they can also provide aesthetic enjoyment, viewing buildings from a distance and a quick grow of the greened surface. The irrigation system which is required for the living wall systems and the especial supporting structures according to each system form also a part of the higher costs.

Maintenance costs

According to Middelie (2009) and Perini et al (2011) the following points are the most costly activities.

- irrigation management system
- the costs of using of boom lifts during pruning phase
- replacing of plants
- replacing of panels
- human activity costs
- collection and disposal of fallen leaves

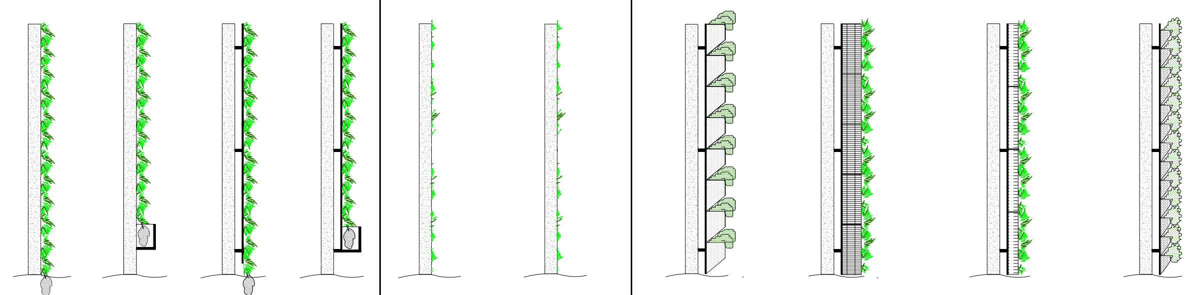
3.3.4 Irrigation systems

The principal aim of irrigation is to ensure that optimum water regimes are maintained within the root zone of plant species. The practical problem that all irrigation scheduling strategies have to contend with is to establish how much water and nutrients should be added to the soil and when this should be done. A continuous assessment of just what plant specie requires is therefore central to the implementation of any efficient water management system.
Establishing appropriate levels of watering and appropriate levels of nutrients are important living aspects which should function continuously. Otherwise it can cause problems by forgetting of service and operating (Yu-Peng yeh, 2010). Irrigation systems are energy consuming which deal with a technique for the continuous monitoring of the moisture regime within the root zone, and is based on deploying a self automated system (Ottelé, 2011).

3.4 Overview of advantages and disadvantages

The general advantages and disadvantages of vertical greening systems are described and explained point by point in paragraphs 3.2 and 3.3. In this part of the report you can find the specific advantages and disadvantage of all the discussed vertical greening systems separately. Table 3.1 gives an overview of the studied vertical greening systems with their advantages and disadvantages.

Table 3.1: the advantages and disadvantages of the vertical greening systems based on literature given in paragraphs 3.2 and 3.3.

vertical green type	**green façade**				**wall vegetation**		**living wall system (LWS)**			
type	direct	direct	indirect	indirect	natural	concrete panel	planter boxes	foam based	mineral wool based	felt layers
schematic representation / **advantages and disadvantages**										
reducing heat island effect (UHI)	xx	xx	xx	xx	x	x	xxx	xxx	xxx	xxx
adsorption fine dust particles	xx	xx	xx	xx	x	x	xxx	xxx	xxx	xxx
increasing of biodiversity	xx	xx	xx	xx	x	x	xx	xx	xx	xx
moderating buildings internal temperature via external shading	xx	xx	xx	xx	x	xx	xxx	xxx	xxx	xxx
sound insulation	xx	xx	xx	xx	x	xx	xxx	xxx	xxx	xxx
creating micro climate	xx	xx	xx	xx	x	x	xx	xx	xx	xx
improved aesthetic value	xx	xx	xx	xx	--	x	xxx	xxx	xxx	xxx
improved insulation property	x	x	x	x	--	--	xx	xx	xx	xx
greening system costs	x	x	xx	xx	--	x	xxx	xxx	xxx	xxx
maintenance costs	x	x	xx	xx	--	--	xxx	xxx	xxx	xxx
irrigation system required	--	x	--	x	--	--	xx	xx	xx	xx
short period of covering	--	x	--	x	--	--	xxx	xxx	xxx	xxx
full covering of the façade	x	x	x	x	--	--	xxx	xxx	xxx	xxx
chance of moisture problems on solid walls (without air cavity)	xx	xx	--	--	x	x	--	--	--	--
penetration of roots in the wall	xx	xx	--	--	xx	xx	--	--	--	--
indoor application	--	--	x	x	--	--	xx	xx	xx	xx
technical expertise needed	--	x	xx	xx	--	xx	xxx	xxx	xxx	xxx
replacement of panels	--	--	--	x	--	--	x	xx	xx	xx
replacement of died plants	--	x	--	x	--	--	xx	xx	xx	xx

x poor
xx good
xxx better
-- not applicable

4 Building physics and vertical greening systems

4.1 Introduction to building physics

Building physics is the application of the principles of physics to improve the built environment. In building physics the state and operation of the building envelope is analyzed (Hagentoft, 2001). This consists of building components such as walls, roofs and foundations. The physical processes in the building envelope components deal with heat, moisture and air transfer. These physical transport processes determine the performance of the building (Tammes and Vos, 1984; Hagentoft, 2001).

4.2 Building physics and vertical green

There are many physical advantages of vertical greening mentioned in paragraph 3.2. The next physical benefits can be mentioned according to paragraphs 3.2.4 and 3.2.8;

Vertical green can:

- moderate a building's internal temperature via external shading
- create a microclimate, which will help to alter the climate of a city as a whole
- help a building retain heat otherwise lost to convection

and many more.

To prove scientifically whether vertical greening has really these physical advantages, it is necessary to measure some vertical greening systems in a laboratory designed climate chamber. The expected performances and the consequences of vertical green designs and technical solutions must be known before important decisions can be taken. Therefore it is necessary to realise a measurement system to measure some vertical green systems in order to get more scientific information about building physics aspects of vertical green in reality. For this purpose a hotbox (experimental setup) is built. The principle of testing in the hotbox is to determine under steady state conditions (laboratory condition) the amount of heat flowing and moisture transport through a test specimen placed between a warm and a cold enclosed enclosure.

4.2.1 Description of hotbox adjustment and measurement procedure

As the name makes it clear, the hotbox is a box which has two compartments. The hotbox is made from plywood (thickness 18 mm) and consists of a so-called ‘outside’ climate chamber and also a so-called ‘inside’ climate chamber and a surround panel with an aperture of 1000 x 1000 mm to mount the sample. Figure 4.1 shows the plan of the hotbox. The hotbox wooden structure has a length of 3000 mm, width of 1800 mm and a height of 1800 mm. The hotbox is insulated from its surroundings with EPS-SE. The SE shows the fireproof and fire retardant quality of the EPS material. The width of EPS insulation inside the hotbox is 200 mm (two layers of 100 mm glued to each other, figure 4.2). The sample aperture is placed at the middle of the hotbox in longitudinal direction. Therefore the outside climate chamber has the same dimensions as the inside climate chamber. This is clear shown on figure 4.1.

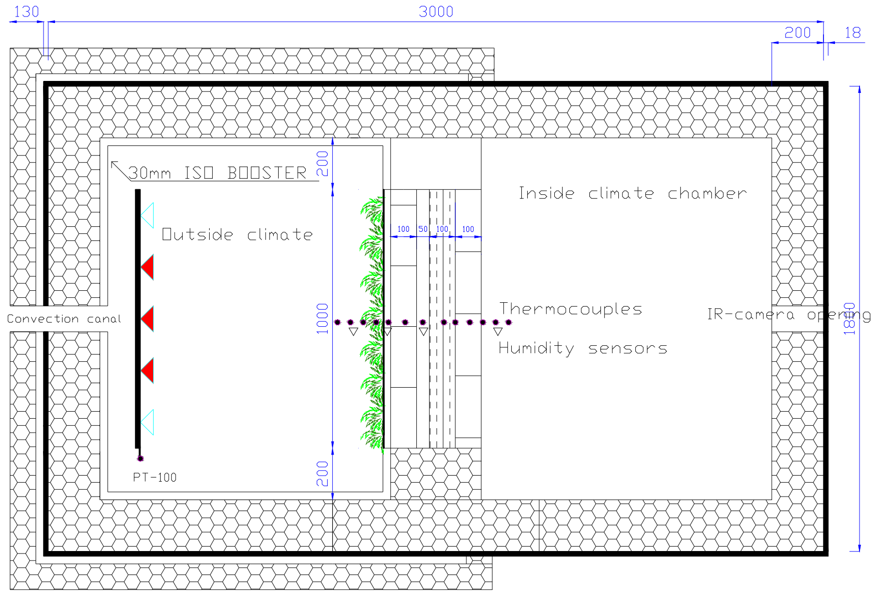


Figure 4.1: hotbox plan (horizontal section) with inside insulation and test specimen with vertical green on it. Dimensions in mm.

Figure 4.2: left, two layers of EPS glued to each other; right, technicians during the building of hotbox.

The objective was to make the hotbox as tight as possible against temperature leakages, and this was made already clear to the technicians. The technicians had joined the corners like figure 4.3a, while it should have been like figure 4.3b. After checking and finding the leakage, it is again explained and the corner solution is changed to a better tightness against temperature losses (figure 4.3b).

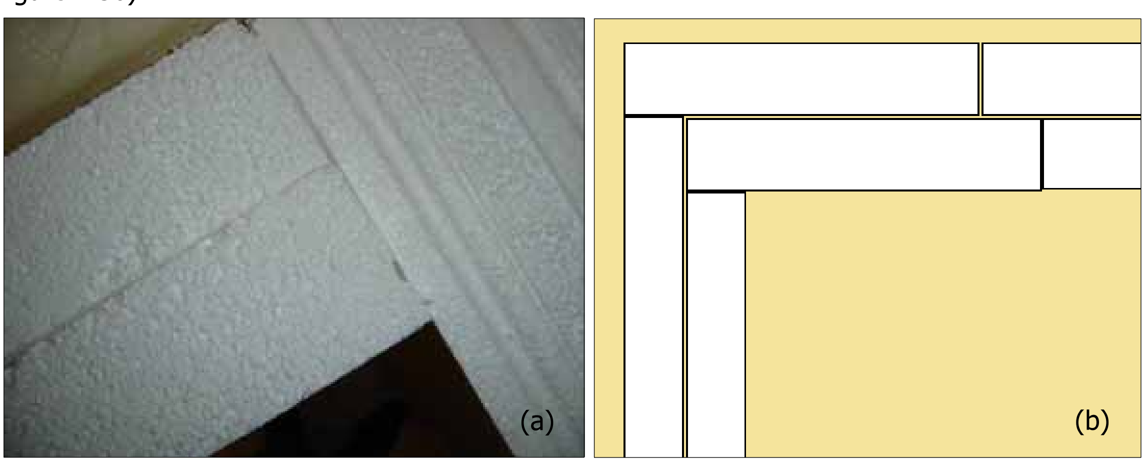
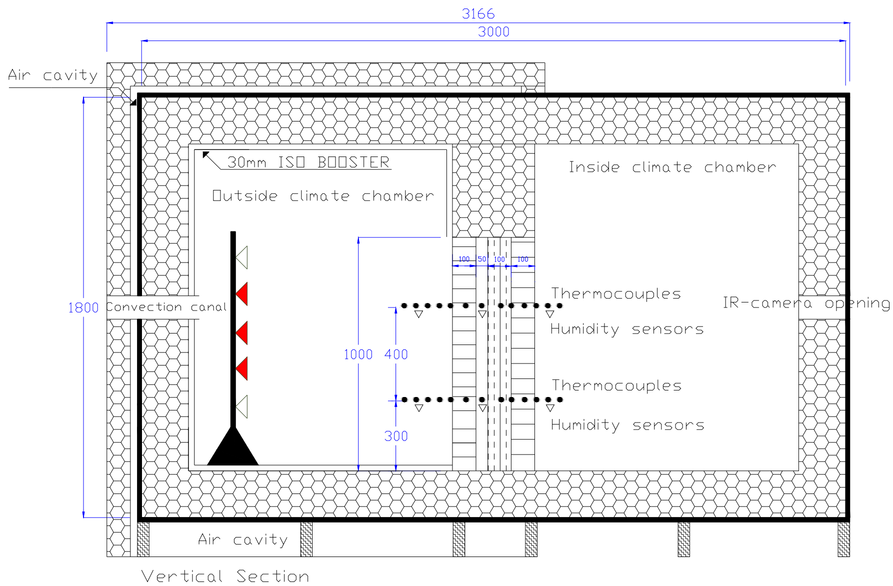


Figure 4.3: (a) fault corner solution with EPS; (b) well connected corner solution with EPS.

To minimise temperature losses during the measurements it was decided to insulate the box also from the outside. This has an effect outside climate chamber (left side on figure 4.4). This insulation layer is also from EPS with a thickness of 100 mm around the hotbox. Between the insulation and the wooden structure there is an air cavity of about 30 mm. The purpose of this outside insulation chamber is to create a layer of air cavity around the hotbox to regulate the temperature in this air cavity (figure 4.5a). The same air temperature in the hotbox and in the air cavity means that the temperature loses will be lowest amount from the hotbox. Also inside the so called outside climate chamber there is an extra insulation layer of Iso-Booster (insulation layers made from aluminium foil and plastic) applied.

Figure 4.4: vertical section of hotbox with inside insulation (Iso-booster), outside insulation (around the outside climate chamber) and the test specimen between the climate chambers. Dimensions in mm.



The measurements are done with a measuring system, which is connected to a computer outside the hotbox (figure 4.5b). Special measurement software saves the data continuously for temperature and humidity.

Figure 4.5: (a) outside EPS-insulation layer with an air cavity around the hotbox; (b) measuring computer outside the hotbox.

4.2.2 The test specimen

The test specimen used for the experiment consists of a wall with a surface of 1 m^2 (made in Dutch building system, figure 4.6a). The test specimen is made from two different brick types (for inner leaf the lime stone- and for the outer leaf clay 'masonry' the normal façade bricks) and a layer of insulation material between the inner leaf and the masonry. A wooden frame structure is made to keep the system stable and compact as one package during the building process and also after that, during the measuring procedures. The test specimen size is w x h = 1000 x 1000 mm and its depth is 350 mm (figure 4.6b). The test specimen has a (inner leaf + insulation + air cavity+ masonry).

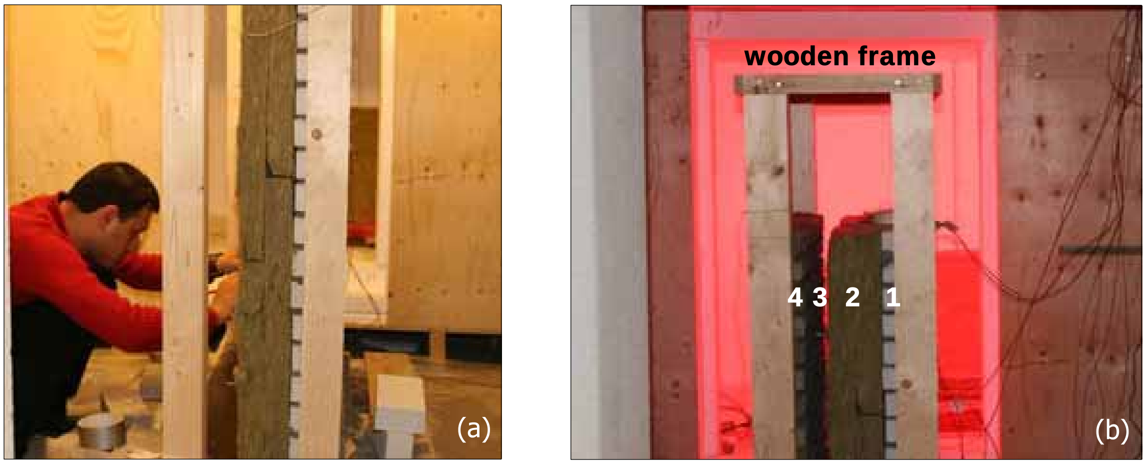
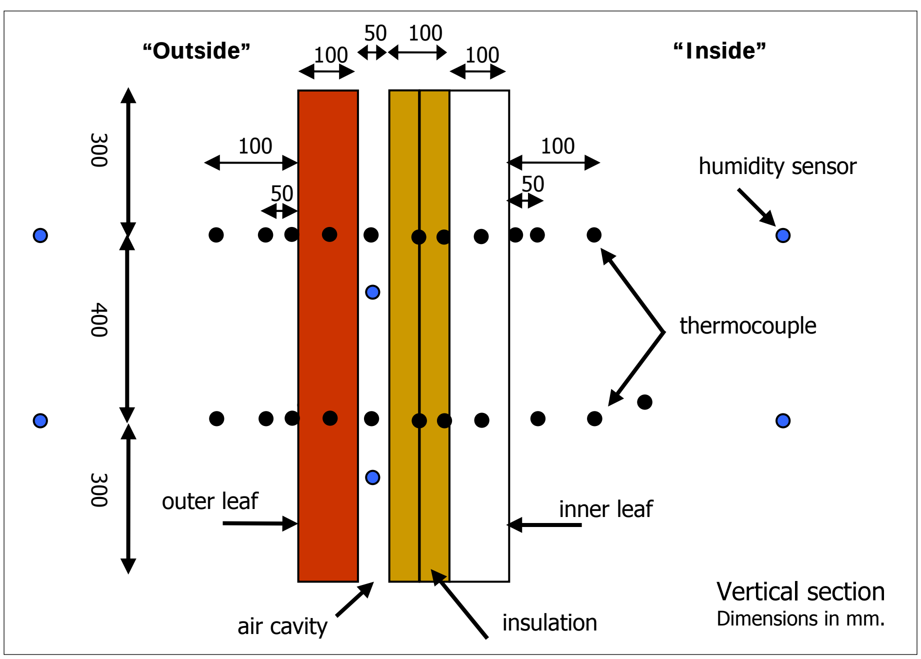


Figure 4.6: (a) the test specimen during the building process; (b) the side view of test specimen: 1- inner leaf; 2- insulation; 3- air cavity and 4- masonry.

During the construction process of the test specimen, there are thermocouples and humidity sensors placed in different positions inside the test specimen in two layers. The measurement takes place across the test specimen from left to right and right to left for both summer and winter condition. Figure 4.7 shows the thermocouples and humidity sensors in two vertical layers of 300 mm from the bottom and 300 mm from the top of the specimen.

Figure 4.7: positioning thermocouples and humidity sensors through the test specimen.



After building and completing the wall as a package, it is ready to place also the thermocouples outside the wall and to put it in the hotbox (figure 4.8).

The description of the used measurement supplies are listed in Annex A.

Figure 4.8: the test specimen before placing in the hotbox.

4.2.3 Testing of the hotbox

After building and completing the hotbox with the test specimen inside it, it was possible to do the first measurements. But unfortunately after the first "*test*" measurements there were some temperature leakages (figure 4.9a, b and c), which had to be corrected. The leakages are detected with infrared camera and they are corrected immediately with PUR and extra insulating materials (figure 4.9d). The purpose of our measurement is to have almost no leakages through the hotbox walls, roof and floor. Therefore it was important to check al of the weak points that could be thought. Iso-booster (insulation material) was a good solution to make the hotbox leakage free from the inside.

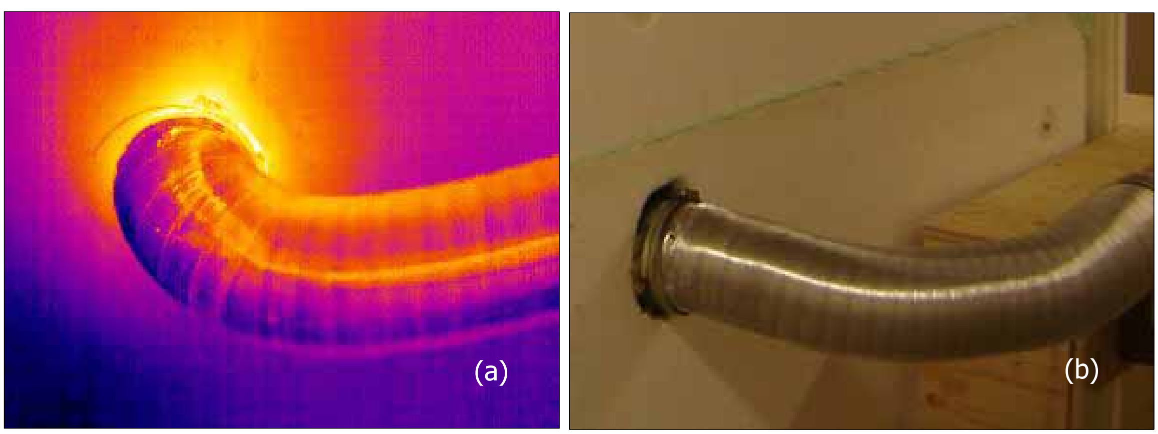


Figure 4.9: (a) leakage by heat input at the entrance to the hotbox; (b) the leakage is repaired with extra insulation material around the aluminium pipe at the entrance.

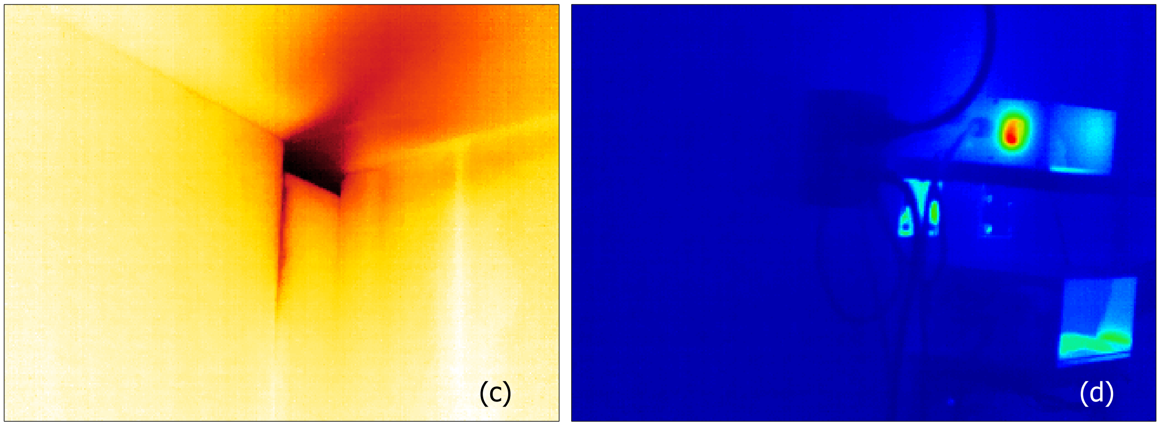


Figure 4.9: (c) leakage inside the hotbox in the corner at the door opening; (d) an infrared photograph after correcting the leakages. It is clear that only the apparatus (Pt-100 and ventilator outside) are warm and no more leakages.

Because of the temperature difference between the hotbox and the basement where the hotbox is located, it was needed to apply also an outside insulation around the hotbox. As it is all discussed, this insulation layer is made of EPS and this creates an air cavity around the hotbox, which can become warmer and colder according to hotbox temperature during the measurements. Also this insulation cover prevents the temperature loses.

The bare wall (wall without any green) is the basis of the measurement procedures. Prior to the green wall system measurement procedures, the bare wall is measured a few times to understand the whole system of measurement better and to discover the weak points. All of the thermocouples, humidity sensors and the software are checked to prevent the faults during the real measurements.

The following vertical greening systems (already mentioned in paragraph 2.3.1) are tested beside the bare wall in the hotbox.

Green façades

1) a wall with self- climbing plants (*Hedera helix*, directly to the wall)
2) a wall with self-climbing plants with supporting structure (*Hedera helix*, indirectly to the wall)

Living wall systems (LWS)

3) LWS based on planter boxes (Greenwavesystem)
4) LWS based on felt layers (Wonderwall of Copijn)
5) LWS based on mineral wool (Wallflore system)
6) LWS based on foam substrate (Fytowall-fytogreen)

After that the tests are performed for various vertical greening systems combined with the bare wall, moisture transport through the total package is calculated, analysed and compared with practice. Chapter 5 describes the moisture and moisture transport calculations.

5 Moisture and moisture transport

5.1 Moisture

According to literature (Linden, 2005; Hagentoft, 2001; Tammes and Vos, 1984), moisture can occur in three aggregation phases:

- gaseous phase (vapour)
- liquid phase (water)
- solid phase (ice)

As much as water is essential for all forms of life it can cause also its own specific problems in the construction industry (Linden, 2005; Hagentoft, 2003). It is not easy to distinguish these three forms of moisture in all processes, and therefore it is used to talk about moisture problem. Moisture transport in a material can only take place if the relevant material is porous and this phenomenon take place by the most of porous materials. Some porous materials like glass foam do not transport moisture, because the water molecules can not find continues paths through the material structure. Non porous material such as glass and metals transport no moisture.
The quantity of moisture in every cubic metre of dry air is known as the absolute air humidity, or the vapour density (c in kg/m³). As well as using the vapour density, you can express the amount of moisture on the basis of its contribution to the total air pressure: the partial vapour pressure (p in N/m² or Pa).

The relationship between vapour density and vapour pressure is shown by the Boyle-Gay Lussac Law (Linden, 2005):

$$p = \frac{m}{V} \cdot R \cdot T \left[\text{Pa}\right]$$

If there is less vapour pressure than the maximum level, this can be expressed in terms of relative humidity (φ). This is the relationship between the prevailing vapour pressure (P) and the maximum possible level of vapour pressure ($P\max$) for that temperature. This relationship is expressed as a percentage (%):

$$\varphi = \frac{P}{P\max} \cdot 100\%$$

The absolute humidity (c in kg/m³) indoors is almost greater than outdoors, and this is because of vapour production through human activity such as washing, breathing, cooking etc. But situation regarding relative humidity is different. The temperature of the space has a big influence on the percentage of relative humidity, the low temperature the high relative humidity, and the high temperature, the low relative humidity.

5.2 Moisture transport, vapour diffusion

The diffusion of vapour (moisture) through building materials is a natural phenomenon. Vapour diffusion is one mechanism whereby water can find its way into the components of a building and damage the materials or assemblies, although it is not the only one. In many instances it may be

of less importance than others such as rain penetration or air leakage which transports water vapour with it.
Water vapour is one of the several gaseous constituents of air, the other principal ones being nitrogen, oxygen and carbon dioxide. Each exerts its own partial pressure in proportion to the amount of gas present, the sum of the pressures making up the total or barometric pressure of the air. When there is a difference in concentration of one of these gases between two points, there will be a corresponding difference in partial pressure. This will cause a flow of that particular gas from the point of higher concentration to the lower. When a partial pressure difference exists between two sides of a material, the gas involved will diffuse through the material until the partial pressures of that gas are equalized. The rate of diffusion will be determined by the partial pressure difference, the length of the flow path, and the permeability to the particular gas involved of the medium through which flow is taking place (Linden, 2005; Hagentoft, 2001; Tammes and Vos, 1984).

Vapour diffusion resistance
The transport of vapour through a construction encounters a certain degree of resistance depending on the type and density of the material. Moisture flow, the difference in vapour pressure and vapour resistance are related as follows:

$$g = \frac{\Delta p}{R_d} \cdot 1000 \left[g / m^2 . s \right]$$

g = the vapour transport in g/m² · s
Δp = the difference in vapour pressure between the inside and outside (Δp = (pi – pe)) in Pa
R_d = vapour diffusion resistance in m/s

The factor of 1000 is added in order to obtain a result in g/m² · s instead of in kg/m² · s.

$$R_d = 5.3 \cdot 10^9 \cdot \mu \cdot d \left[m / s \right]$$

d = the thickness of the layer of material in [m]

Diffusion resistance figure
The vapour density of various materials is expressed using the vapour diffusion resistance figure (μ). This indicates how many times greater the diffusion resistance is of a layer of material than of a layer of air of the same thickness. As a formula, the definition is as follows:

$$\mu = \frac{\text{vapour diffusion resistance of a layer of material}}{\text{ditto, for a layer of air of identical thickness}}$$

Progression of vapour pressure in a construction
To calculate the vapour diffusion resistance of the layer, the formula becomes:

$$\Delta p_n = \Delta p \cdot \frac{\mu \cdot d_n}{\mu \cdot d_{tot}} \left[Pa \right]$$

It can clearly be seen here that the $5.3 \cdot 10^9$ value is omitted and that we can only use the μ · d values, as this concerns the relationship between the levels of vapour resistance of the different layers.

5.3 Internal condensation; Glaser method

In the last few paragraphs, the progression of vapour density through a structure is made clear, and it was without any consideration of progression of temperature and condensation between the layers. For determining internal condensation it is necessary to look also at the progression of temperature through the structure. The progression of the maximum vapour pressure in the structure (p_{max}) can be determined from the progression of the temperature through the structure. For every temperature, there is a maximum level of vapour pressure in literature (annex C). Actually the calculated vapour pressure (p_{calc}) should not be higher than the maximum vapour pressure. When the calculated present vapour pressure exceed the maximum vapour pressure for the given temperature, then condensation can occur in the structure (see tables 5.1-5.13 for the different systems).

Internal condensation in the structure should be prevented or limited because:

- the construction may start to rot
- there is a chance of damage caused by freezing
- too much moisture reduces heat resistance

To protect the structures against the condensation, it is important that the amount of moisture which is produced in the winter period should evaporate in the summer. That means that $g_{summer} \geq g_{winter}$. By the calculations with the Glaser method it is assumed that the values for g_{winter} are representative for the condensation by variable climate conditions. The following limitations may be held for calculations (Schuur, 2000).

- insulation material in the structures $g_{winter} \leq 500 g/m^2$.
- not moisture-absorbing insulation material $g_{winter} \leq 100 g/m^2$.

Glaser method (Linden, 2005; Hagentoft, 2001; Tammes and Vos, 1984) can be applied to calculate the condensation occurring through the structure with green on it.

5.4 Moisture in relation with vertical green

As it is made clear in the literature (Hermy, 2005; Anonyms, 2002), vertical greening systems such as self climbing plants work as a rain protector. The cause of moisture on the walls is usually heavy rains during the autumn and winter, but in the case of vertical green on the wall the foliage prevents the wall from directly rain. This means that walls with vertical green on it, are dryer than without vertical green (figure 5.1). If the whole surface of the wall is not protected with green (bare spots almost in case of young plants), than there is the chance that the wall become locally wet.

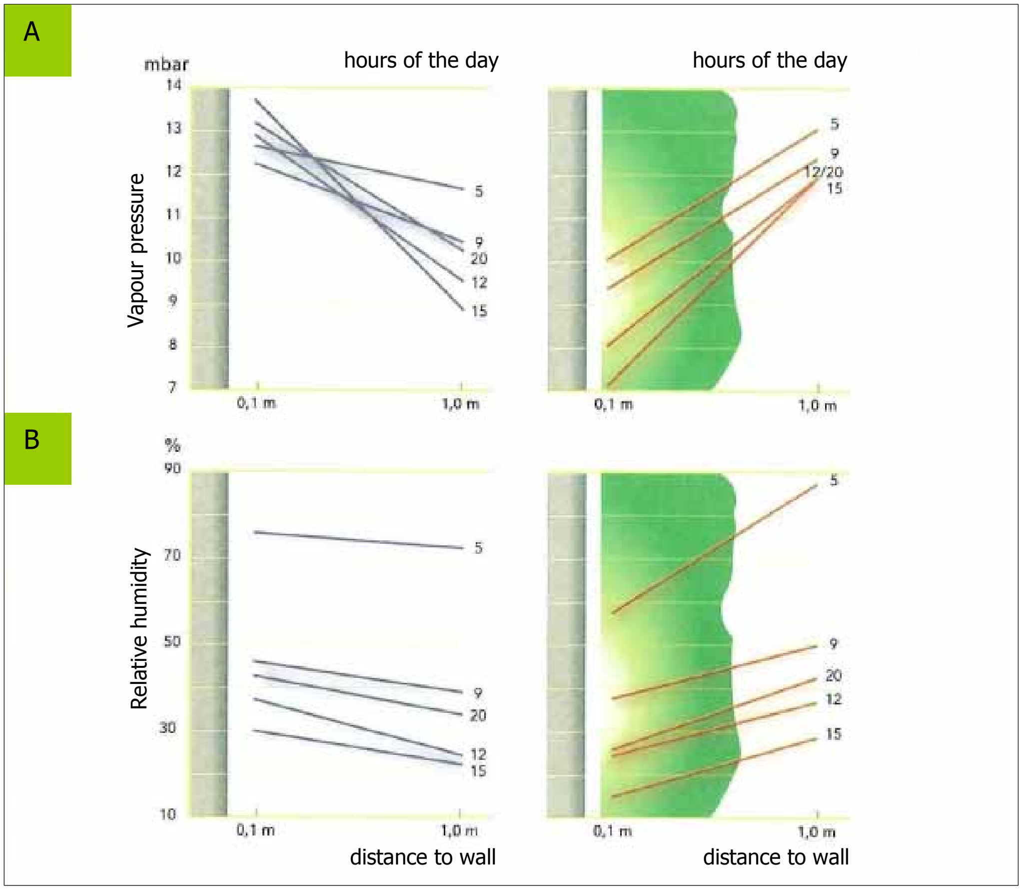


Figure 5.1: gradients in humidity in relation to the distance to the wall (left) non greened façade and (right) greened façade at different times of day (source: Hermy, 2005; Köhler, 1993; Bartfelder and Köhler, 1987). A- Vapour pressure and B- relative humidity.

But where the moisture is resulting from the rising ground water by old walls, the vertical green prevents the evaporation of the moisture from the wall and the result can be a humid wall. The essential reason of this is not the plants but the open contact of the wall with the foundation (figure 5.2). If a wall is humid and the moisture cannot dry rapidly, it can cause mould, pests, damage to the material covers and health problems inside the building (figure 5.3).

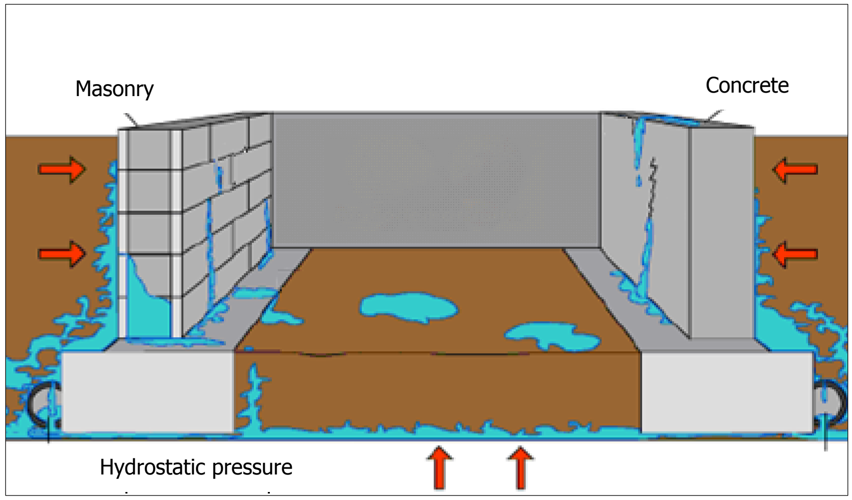


Figure 5.2: open contact between foundation and the façade with applying vertical green against the façade, the wall cannot evaporate capillary moisture rapidly (source: devochtbestrijder.nl).

Figure 5.3: damage inside the building because of humid walls (source: www.devochtbestrijder.nl).

Another point is that the climbers which are losing their leaves (deciduous) in the winter are less effective in case of rain protection. But *Hedera helix* and other evergreen plant species are clearly better because of evergreen characteristic and rain protection (figure 5.4).

Figure 5.4: evergreen plants protect the building against the rain in all seasons (source: www.tomgarden.nl).

As it is already discussed in chapter 2, living wall systems are hanging with a small distance from the wall which means that there is always an air cavity present between the wall and the living wall system. As the living wall systems have a more or less closed set-up at the backside, they protect the wall completely against the direct sun, rain and snow. This is one of the important advantages of living walls in the case of direct rain and snow protection.

5.5 Measuring principle in a designed climate chamber (hotbox)

The intention is to look to the moisture diffusion and to its transport through the bare wall and the bare wall combined with different vertical greening systems on it. The purpose is to find the differences of the tested systems compared to the bare wall. The test results show a laboratory situation with almost no ventilation and no vapour production (human activity) inside the hotbox in both climate chambers. As it is already mentioned the hotbox (test apparatus) is placed in the basement of the Stevin II laboratory of the Faculty of Civil Engineering, and the initial situation of each measurement (temperature and moisture content) is depending on the situation at that time in the basement. The moisture content of the hotbox in two climate chambers and through the bare wall and vertical green systems is measured with humidity sensors, which are translated and calculated in relative humidity percentages.

5.5.1 Determination of the tested systems for calculating moisture transport

As it is already mentioned, seven systems are measured in the hotbox which is a part of the PhD project of Ottelé (2011). In this Master graduation project, only four systems will be taken into account to determine the moisture transport through them (see paragraph 2.3). The chosen systems will be studied for both summer and winter situations. The next systems will be determined and calculated.

- Bare wall
- *Hedera helix* direct to the wall
- *Hedera helix* indirect to the wall
- LWS based on planter boxes

5.5.2 Summer and winter measurements

The measurements are applied for both summer and winter conditions. The calculations are listed in tables (below) with the following formulas from part 4.3.

This formula $\Delta p_n = \Delta p \cdot \frac{\mu \cdot d_n}{\mu \cdot d_{tot}} [Pa]$ is used for condensation and this formula

$g = \frac{\Delta p}{R_d} \cdot 1000 \left[g / m^2 . s \right]$ is used for diffusion.

Symbols used in table:

- d(m) thickness layer
- ΔT (°C) the difference temperature between the measuring points beside each other
- T (°C) temperature (measured during the experiment)
- P_{max} (Pa) maximum vapour pressure from the table (annex C)
- μ (-) vapour diffusion resistance figure
- μ.d (m)
- Δp (Pa) the difference in vapour pressure
- P_{calc} (Pa) calculated vapour pressure on layers
- RH (%) relative humidity (measured during the experiment)

Determining of μ (vapour diffusion resistance figure) for greening layer

As an extended literature survey shows, there is probably no μ-figure determined for vegetation as green layers (μ-figure indicates how many times greater the diffusion resistance is of a layer of material than of a layer of air of the same thickness). According to Schuur (2000) the smallest μ-figure that can be found is between 1 and 2, which is valid for insulation materials (mineral wool). The vapour diffusion resistance figure for moisture transport for all materials should be greater than for air. That means μ≥1 (Schuur, 2000).

If we compare insulation material with a green (vegetation) layer of about 10 to 15 cm, than it is possible to assume that a mineral insulation material has more resistance than a vegetation layer. Vegetation layers are more porous, besides it produces vapour by evapotranspiration. Losing vapour (evaporation) depends to the kind of plant species, the amount of water given to plant and how much water the roots of the plant can absorb. It depends also on environmental conditions as light intensity, humidity, wind and temperature.

To have an idea how plant species could react by condensation and diffusion, we make an assumption for determining the μ-figure for vegetation during the measurements in the hotbox facility. After searching, studying and comparing a vegetation layer with 'for example' insulation material, it can be concluded that a μ-figure between 1 and 2 can be used for vegetation layers. In the following tables (5.1, 5.2, 5.4, 5.5, 5.8, 5.10-5.13) a μ-figure of **1.5** is assumed to calculate the moisture transport.

Determining the μ (vapour diffusion resistance figure) for substrate (growing media used for a living wall).

To calculate the condensation between the layers of a living wall system based on planter boxes and the wall, it is needed to determine the vapour diffusion resistance (μ-figure) for substrate (soil). After studying literature so far, it becomes clear that there is not a μ-figure for wet soil.

When we look to the structure of planter boxes (figure 5.5 in this chart), the soil is in every box and at two sides covered with a (HDPE) layer, which has a very high (9000) μ-figure. (a high μ-figure means that the vapour transport is very slow and even impossible). In this case we make an assumption to say that the contribution of soil by transporting vapour is nil, because the soil is protected between two layers of (HDPE).

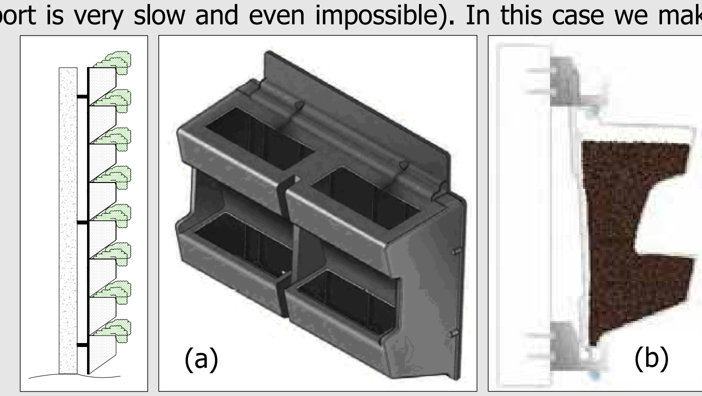


Figure 5.5 : left; principle of planter boxes (a) module of planter boxes and (b) the section of a planter box with growing media (soil) in it (source: www. greenwavesystems.eu).

5.5.3 Calculation of condensation for summer measurements

The summer measurements are applied for 8 hours during the day period. The 8 hour (during the day) procedure is chosen because of safety reasons associated with fire, overheating, etc. The average amount of sunny hours in the summer in Netherland is 655,4 hours. This corresponds to 7,2 hour per day in the summer (www.KNMI.nl/zomer in Nederland) The average temperature in the summer in Europe is 19,7°C, and the maximum can reach 42°C (www.KNMI.nl/zomer in europa). All of the summer measurements are occurred with a maximum temperature of 35°C which is corresponding with a "normal" summer shiny day in the most of

European countries. The measuring system is automatically switched off through a Pt-100 during the 8 hours. The condensation and diffusion calculations are taken place after 8 hour procedure and they are listed in tables.

Table 5.1: calculation of the progression of vapour density in the bare wall for summer measurement.

Bare wall									
Structure thickness	d	ΔT	T	p_{max}	μ	μ.d	Δp	p_{calc}	RH
in	m	°C	°C	Pa		m	Pa	Pa	%
outdoor air			34.84	5559				2724	49
re		2.21			-	-	-		
			32.63	4917				2724	
masonry	0.1	1.34			9	0.9	350		
			31.29	4569				2374	
air cavity	0.05	1.19			-	-	-		
			30.1	4266					
insulation material	0.1	5.56			2	0.2	78		
			24.54	3073				2297	
limestone	0.1	0.29			12	1.2	466		
			24.25	3037				1831	
ri		0.12			-	-	-		
indoor air			24.13	3001				1831	61
Total						2.3	893.3		

As it can be seen in table 5.1 the calculated vapour pressure (p_{calc}) on layers of the bare wall is not higher than the maximum vapour pressure (p_{max}). According to the Glaser method, it means that there is no condensation between the layers of the bare wall.

Table 5.2: calculation of the progression of vapour density in the wall + Hedera helix direct to the wall for summer measurement.

Hedera helix direct to the wall									
Structure thickness	d	ΔT	T	pmax	μ	μ.d	Δp	pcalc	RH
in	m	°C	°C	Pa		m	Pa	Pa	%
outdoor air			34.08	5347				5240	98
re		1.77			-	-	-		
			32.31	4835				5240	
Hedera helix foliage	0.2	0.35			**1.5**	0.3	405		
			31.96	4653				**4835**	
masonry	0.1	1.01			9	0.9	1215		
			30.95	4491				3620	
air cavity (wall)	0.05	1.4			-	-	-		
			29.55	4145					
insulation material	0.1	0.97			2	0.2	270		
			28.58	3913				3350	
limestone	0.1	4.66			12	1.2	1620		
			23.92	2983				1730	
ri		0.11			-	-	-		
indoor air			24.03	2983				1730	58
Total						2.6	3509.9		

Table 5.2 shows that the calculated vapour pressure (p_{calc}) between the green layer (*Hedera helix* directly to the wall) and the wall surface is higher than the maximum vapour pressure (p_{max}) at that point. In this case there is condensation on the exterior surface of the wall. The reason for the condensation at outside climate chamber is probably the high relative humidity (RH) at the beginning of the measurement and also after 8 hours. The relative humidity was 98%. As it is already mentioned the measurements are performed under the laboratory condition but in case of a normal outdoor condition the relative humidity will be lower (70%-80%). With low relative humidity of (for example) 75%, the calculated vapour pressure (p_{calc}) will be always lower than the maximum vapour pressure (p_{max}) which is beneficial for normal outdoor conditions (table 5.4). Another point which can have influence on the condensation is the variable μ (vapour diffusion resistance figure) for the vegetation. The μ-figure for vegetation layer can be assumed between 1 and 2, and in all cases the calculated vapour pressure is higher than the maximum vapour pressure for (RH=98%). That means that the influence of μ-figure is not determinative for the condensation (table 5.3).

Table 5.3: calculation of vapour pressure with variable μ-figure for plants according to table 5.2.

μ-figure	p_{calc} [Pa]	p_{max} [Pa]
1	4959	4653
1.1	4934	4653
1.2	4908	4653
1.3	4884	4653
1.4	4859	4653
1.5	**4835**	**4653**
1.6	4811	4653
1.7	4788	4653
1.8	4765	4653
1.9	4742	4653
2	4720	4653

Table 5.4: calculation of the progression of vapour density in the wall + Hedera helix direct to the wall for summer measurement with an adapted relative humidity of 75%.

Hedera helix direct to the wall									
Structure thickness	d	ΔT	T	pmax	μ	μ.d	Δp	pcalc	RH
in	m	°C	°C	Pa		m	Pa	Pa	%
outdoor air			34.08	5347				4010	75
re		1.77			-	-	-		
			32.31	4835				4010	
Hedera helix foliage	0.2	0.35			**1.5**	0.3	263		
			31.96	4653				3747	
masonry	0.1	1.01			9	0.9	789		
			30.95	4491				2958	
air cavity (wall)	0.05	1.4			-	-	-		
			29.55	4145					
insulation material	0.1	0.97			2	0.2	175		
			28.58	3913				2782	
limestone	0.1	4.66			12	1.2	1052		
			23.92	2983				1730	
ri		0.11			-	-	-		
indoor air			24.03	2983				1730	58
Total						2.6	2280.1		

Table 5.5: calculation of the progression of vapour density in the wall + Hedera helix indirect to the wall for summer measurement.

Hedera helix indirect to the wall									
Structure thickness	d	ΔT	T	pmax	μ	μ.d	Δp	pcalc	RH
in	m	°C	°C	Pa		m	Pa	Pa	%
outdoor air			33.82	5259				4312	82
re		1.25			-	-	-		
			32.57	4917				4312	
Hedera helix foliage	0.1	0.58			**1.5**	0.15	158		
			32.63	4917				4154	
air cavity	0.05	1.85			-	-	-		
			31.99	4653					
masonry	0.1	1.21			9	0.9	948		
			30.78	4440				3206	
air cavity (wall)	0.05	0.76			-	-	-		
			30.02	4242					
insulation material	0.1	0.82			2	0.2	211		
			29.2	4051				2996	
limestone	0.1	4.01			12	1.2	1264		
			25.19	3204				1731	
ri		0.33			-	-	-		
indoor air			24.86	3148				1731	55
Total						2.45	2581		

The calculated vapour pressure (p_{calc}) in table 5.5 for *Hedera helix* indirectly to the wall is in all of the layers lower than the maximum vapour pressure (p_{max}). As we discussed in case of a bare wall, this is again according to the Glaser method without condensation. The difference between the measured relative humidity and the normal outdoor relative humidity (75%) is in this case small. The calculations with a 75% relative humidity for outdoor situations have no influence and the condensation does not take place.

The measurement for LWS based on planter boxes (table 5.7) shows that on one point the calculated vapour pressure (p_{calc}) is higher than the maximum vapour pressure (p_{max}), and that is between the vegetation layer and the HDPE layer. Actually this condensation point is not important for the structure of the wall because this is outside the wall. The variable μ-figure for plants does not change the situation significantly. With all of μ-figures between 1 and 2 the calculated vapour pressure stays higher than the maximum vapour pressure between the vegetation and the surface of the wall (table 5.6).

Table 5.6: calculation of vapour pressure with variable μ-figure for plants according to table 5.7.

μ-figure	p_{calc} [Pa]	p_{max} [Pa]
1	4497	4340
1.1	4496	4340
1.2	4496	4340
1.3	4495	4340
1.4	4495	4340
1.5	**4494**	**4340**
1.6	4493	4340
1.7	4493	4340
1.8	4492	4340
1.9	4492	4340
2	4491	4340

Table 5.7: calculation of the progression of vapour density in the wall +LWS based on planter boxes for summer measurement.

Living wall system based on planter boxes									
Structure thickness	d	ΔT	T	pmax	µ	µ.d	Δp	pcalc	RH
in	m	°C	°C	Pa		m	Pa	Pa	%
outdoor air			34.83	5559				4503	81
re		0			-		-		
			34.83	5559				4503	
plant specie	0.1	4.44			**1.5**	0.15	9		
			30.39	4340				**4494**	
substrate	0.2	1.55			-	-	-		
			28.84	3958					
Planter box (HDPE)	0.004	2.66			9000	36	2128		
			26.18	3400				2366	
air cavity	0.05	2.66			-	-	-		
			24.68	3110					
masonry	0.1	1.5			9	0.9	53		
			26.67	3502				2313	
air cavity (wall)	0.05	1.99					-		
			26.3	3420					
insulation material	0.1	0.37			2	0.2	12		
			24.54	3073				2301	
limestone	0.1	1.58			12	1.2	71		
			24.72	3037				2230	
ri		0.37			-		-		
indoor air			24.35	3055				2230	73
Total						38.45	2272.6		

5.5.4 Calculation of vapour diffusion for the summer measurements

The diffusion through the test specimen is calculated for all four chosen systems. The diffusion is calculated with the given formula in table 5.8.

Table 5.8: calculation of vapour diffusion through the wall structure per day for the summer measurement.

The measured (greening) façades	Diffusion; $g = \frac{\Delta p}{R_d} \cdot 1000 \left[g / m^2.day \right]$
Bare wall	-6.33
Hedera helix direct to the wall	-19.88
Hedera helix indirect to the wall	-17.17
Planter boxes systems (LWS)	-0.96

The calculated amount of diffusion for the summer measurements has minus values. That means that the diffusion is taken place from outside climate chamber (outdoor) to inside climate chamber (indoor). The following figure 5.6 shows the calculation for 90 days during the summer and the formulas in paragraph 5.4 show the limitation for vapour diffusion which will be calculated for summer and winter measurements.

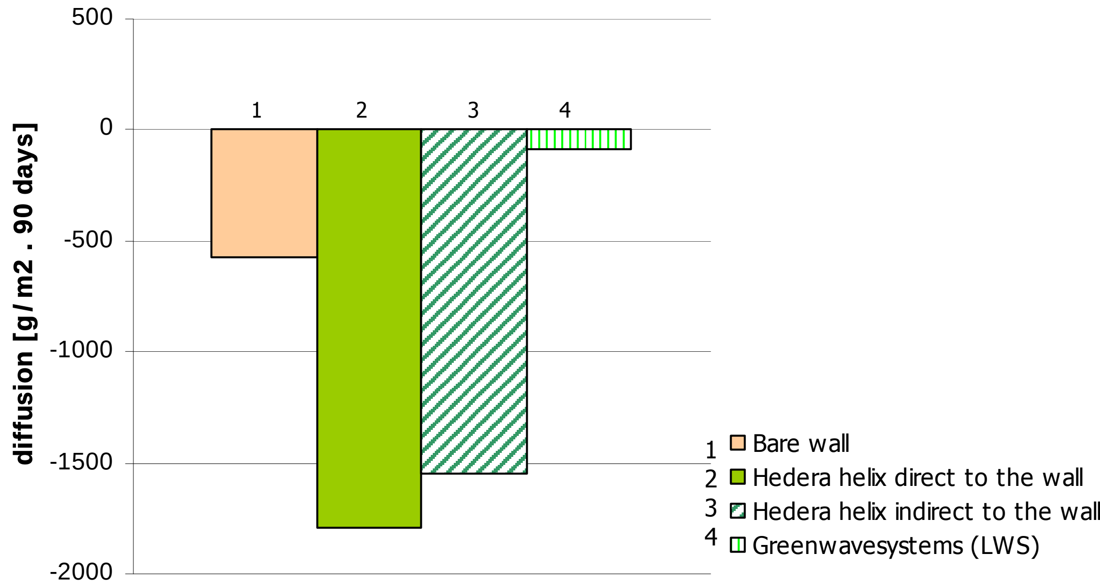


Figure 5.6: diffusion through the test specimen, for bare wall and different greening systems during the summer (90 days).

As it is visible in figure 5.6, vapour diffusion during the summer measurement for *Hedera helix* direct and indirect to the wall has larger values than the bare wall compared with LWS. This can conclude that a direct contact of the plant specie with the façade without an air cavity can cause more vapour diffusion. A living wall system with an air cavity and closed structure to the façade protects the façade against vapour diffusion. This is one of the advantages of living wall systems as shown with this calculation.

5.5.5 Calculation of condensation for the winter measurements

The average winter temperature in Europe is determined between -0,2°C and 2,4°C in the last years while the lowest temperature has reached -18,4°C (www.KNMI.nl/winter temperatuur europa). The winter measurements are applied for 72 hours. The 72 hour procedure is chosen because of reaching of a freezing temperature (winter) in the outside climate chamber for measuring the vertical greening systems. All of the winter measurements are occurred with a minimum temperature of -5°C up to -10°C which is reached in the outside climber chamber. The reached temperature of -5°C up to -10°C is corresponding with a freezing winter day in the most of European countries.
The condensation and diffusion calculations are taken place in the same way as the summer measurements. Winter measurements are performed according to 72 hour procedure and they are listed in the tables below.

Table 5.9: calculation of the progression of vapour density in the bare wall for the winter measurement.

Bare wall									
Structure thickness	d	ΔT	T	p_{max}	μ	μ.d	Δp	p_{calc}	RH
in	m	°C	°C	Pa		m	Pa	Pa	%
outdoor air			-7.62	321				132	41
re		2.21			-	-	-		
			-6.64	350				132	
masonry	0.1	1.34			9	0.9	269		
			-2.35	500				401	
air cavity	0.05	1.19			-	-	-		
			0.81	647					
insulation material	0.1	5.56			2	0.2	60		
			17.05	1949				461	
limestone	0.1	0.29			12	1.2	359		
			17.65	2024				820	
ri		0.12			-	-	-		
indoor air			17.85	2050				820	40
Total						2.3	688		

The calculated vapour pressure (p_{calc}) through the layers of the bare wall for the winter measurement shows that the maximum vapour pressure by the given temperatures are not exceed (table 5.9). According to the Glaser method, there is no condensation between the layers.

The following table (table 5.11) shows the calculation for the wall combined with *Hedera helix* direct against the façade during the winter measurement. As it is visible, the calculated vapour pressure (p_{calc}) is higher than the maximum vapour pressure (p_{max}) between the masonry layer and the insulation material. This means that condensation has occurred between the masonry and insulation material. One of the factors that can play a role is μ-figure for vegetation layer. But after checking of this factor it is became clear that by every value of μ between 1 and 2, the condensation can not be prevented (table 5.10). To avoid condensation, it is necessary (advisable) to apply a vapour barrier.

Table 5.10: calculation of vapour pressure with variable μ-figure for plants according to table 5.11.

μ-figure	p_{calc} [Pa]	p_{max} [Pa]
1	468	405
1.1	471	405
1.2	473	405
1.3	476	405
1.4	479	405
1.5	**481**	**405**
1.6	484	405
1.7	486	405
1.8	489	405
1.9	491	405
2	494	405

Table 5.11: calculation of the progression of vapour density in the wall + Hedera helix direct to the wall for the winter measurement.

Hedera helix direct to the wall									
Structure thickness	d	ΔT	T	pmax	μ	μ.d	Δp	pcalc	RH
in	m	°C	°C	Pa		m	Pa	Pa	%
outdoor air			-6.19	365				197	54
re		0.03			-	-	-		
			-6.16	362				197	
Hedera helix foliage	0.2	0.26			**1.5**	0.3	71		
			-6.42	356				268	
masonry	0.1	1.51			9	0.9	213		
			-4.91	405				**481**	
air cavity (wall)	0.05	4.43			-	-	-		
			-0.48	586					
insulation material	0.1	3.09			2	0.2	47		
			2.61	736				529	
limestone	0.1	16.57			12	1.2	284		
			19.18	2210				813	
ri		0.69			-	-	-		
indoor air			19.87	2322				813	35
Total						2.6	616		

Table 5.12: calculation of the progression of vapour density in the wall + Hedera helix indirect to the wall for the winter measurement.

Hedera helix indirect to the wall									
Structure thickness	d	ΔT	T	pmax	μ	μ.d	Δp	pcalc	RH
in	m	°C	°C	Pa		m	Pa	Pa	%
outdoor air			-5.94	371				200	54
re		0.09					0		
			-6.03	368				200	
Hedera helix foliage	0.1	0.7			**1.5**	0.15	76		
			-6.73	347					
air cavity		2.01							
			-4.72	412				276	
masonry	0.1	4.54			9	0.9	457		
			-0.18	601				**733**	
air cavity (wall)	0.05	3.32							
			3.14	763					
insulation material	0.1	16.85			2	0.2	101		
			19.99	2337				834	
limestone	0.1	0.71			12	1.2	609		
			20.7	2440				1443	
ri		0.58							
indoor air			21.28	2532				1443	57
Total						2.45	1243		

After calculation of the progression of the vapour density through a wall with vegetation indirectly to the façade (table 5.12), it can be observed that there is again condensation between the masonry and insulation material layer. If the calculations will be performed with a higher relative humidity value for winter outdoor situations, than the measured values, the calculated vapour pressure (p_{calc}) will be much higher than the maximum vapour pressure (p_{max}). To prevent this situation, using of a vapour barrier is advisable.

Table 5.13: calculation of the progression of vapour density in the wall + planter boxes system (LWS) for the winter measurement.

Living wall system based on planter boxes									
Structure thickness	d	ΔT	T	pmax	μ	μ.d	Δp	pcalc	RH
in	m	°C	°C	Pa		m	Pa	Pa	%
outdoor air			-2.09	513				292	57
re		0			-	-	-		
			-2.09	513				292	
plant specie	0.1	0.88			**1.5**	0.15	4		
			-2.97	475				297	
substrate	0.2	1.75			-	-	-		
			-1.22	553					
Planter box (HDPE)	0	4.61			9000	36	777		
			3.39	779				**1073**	
air cavity	0.05	0.6			-	-	-		
			3.99	813					
masonry	0.1	3.54			9	0.9	19		
			7.53	1036				**1093**	
air cavity (wall)	0.05	1.96			-	-	-		
			9.49	1186					
insulation material	0.1	10.21			2	0.2	4		
			19.7	2294				1097	
limestone	0.1	0.29			12	1.2	26		
			19.99	2337				1123	
ri		0.02			-	-	-		
indoor air			20.01	2337				1122	48
Total						38.45	830		

The condensation calculation in the case of table 5.13 for measuring of LWS based on planter boxes shows that there is condensation on two places (between three layers; LWS, the masonry and the insulation material). Condensation between the LWS and masonry is not a significant problem, because this is outside the wall structure, while the condensation between the masonry and the insulation material should be prevented. With a relative humidity of higher than 57% the problem increases, and again it is advisable to use a vapour barrier.

5.5.6 Calculation of vapour diffusion for the winter measurements

Vapour diffusion through the vertical greening systems is calculated for winter measurements and listed in table 5.14.

Table 5.14: calculation of diffusion through the wall structure per day by the winter measurement

The measured (greening) façades	Diffusion; $g = \frac{\Delta p}{R_d} \cdot 1000 \left[g / m^2 .day \right]$
Bare wall	4.88
Hedera helix direct to the wall	3.86
Hedera helix indirect to the wall	8.27
Planter boxes systems (LWS)	0.35

The calculated amount of vapour diffusion for the winter measurements has positive values. That means that the vapour diffusion is taken place from the inside climate chamber (indoor) to the outside climate chamber (outdoor).

The following figure (5.7) shows the calculation for 60 days during the winter.

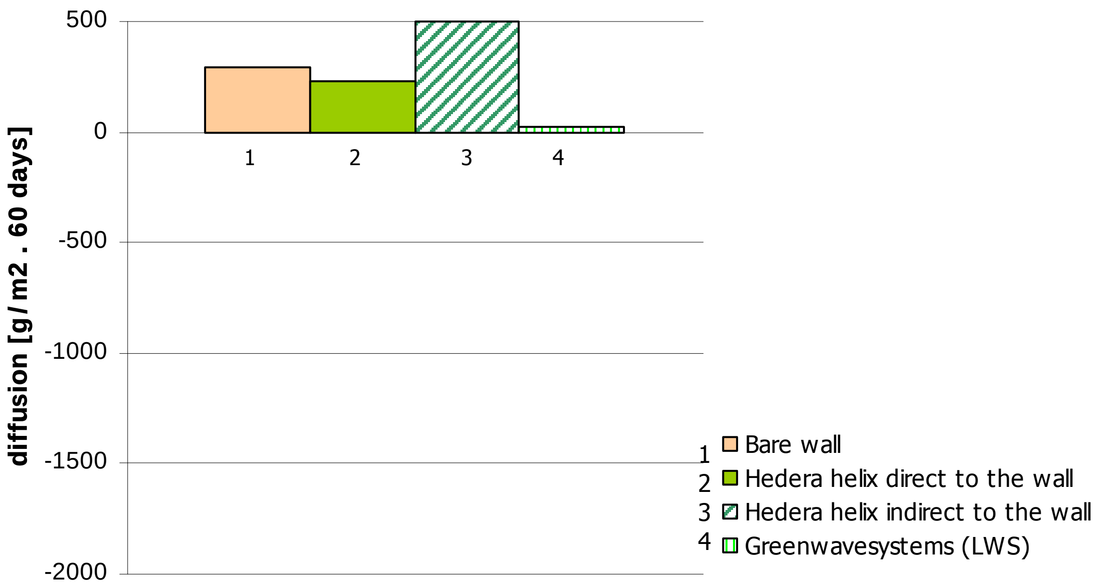


Figure 5.7: vapour diffusion through the test specimen, for bare wall and different greening systems during the winter (60 days).

After calculation of vapour diffusion for 60 days we can see that the calculated values for all vertical greening systems are between 0 and 500g/m^2 which is favourable and according to the regulations. Paragraph 5.4 describes the formulas and limitations for internal condensation. According to Schuur (2000) a wall structure with insulation material should comply with this:

$$g_{\text{winter}} \leq 500 g / m^2 .$$

5.5.7 The effects of these measurements in practice

The following table shows summery of the measured vertical greening systems with results according to the Glaser method and the effects of vertical greening systems in practice. The effects are listed below.

Table 5.15: the results of moisture transport for the calculated vertical greening systems.

	The measured vertical (greening) systems			
Measurements	Bare wall	*Hedera helix* direct to the wall	*Hedera helix* indirect to the wall	Living wall system
Summer measurement (condensation)	1) there is no condensation occurred	2) only condensation between masonry and vegetation layer	3) there is no condensation occurred	4) only condensation between masonry and LWS vegetation layer
Summer measurement (vapour diffusion) $g_{\text{summer}} \geq g_{\text{winter}}$	5) g_{summer}=569g/m^2	6) g_{summer}=1789g/m^2	7) g_{summer}=1545g/m^2	8) g_{summer}= 86g/m^2
winter measurement (condensation)	9) there is no condensation occurred	10) there is condensation between masonry and insulation layer	11) there is condensation between masonry and insulation layer	12) there is condensation between planter boxes-masonry and masonry-insulation material
winter measurement (vapour diffusion) $g_{\text{winter}} \leq 500g/m^2$	13) g_{winter}= 292g/m^2	14) g_{winter}= 231g/m^2	15) g_{winter}= 496g/m^2	16) g_{winter}= 21g/m^2

1) The bare wall is measured as a basis for all of measurements. The relative humidity during the measurement is more or less the same as in practice during the summer. Vapour diffusion meets the requirements.
2) Because of vertical greening directly on the façade and high relative humidity there is condensation on the masonry layer outside the wall structure. This can have almost no negative effects to the wall structure because this is outside and there will be no rot or damage.
3) There is no condensation, and that means that in this case the air cavity between the vertical greening and the façade ensures better ventilation and evaporation of vapour.
4) The more or less air tight texture of the living wall system and high relative humidity during the measurement cause condensation. In comparing to the other vertical greening systems the evaporation is slowly and less rapid.
5) , 6) and 7) The amount of vapour diffusion is between the limitations, according to the Glaser method.
8) Comparing to the bare wall and the other measured vertical greening systems the vapour diffusion is less in this case. This is because of the air tight texture of the living wall system.
9) The bare wall is measured as a basis for all of measurements. The relative humidity during the measurement is more or less the same as in practice during the winter. Vapour diffusion meets the requirements.
10) and 11) The condensation performs inside the wall structure between the masonry and insulation material. A higher relative humidity as in practice has only negative effect no condensation. If the amount of vapour in the winter is more than 500g/m^2

than there should be a solution against the condensation. In this case the condensation in the summer is more than in winter and this means that the condensation is between the limitations. For security reasons a vapour barrier is recommended.

12) The condensation outside the wall structure is not a threatening factor. But when the condensation performs inside the wall structure between the masonry and insulation material, there should be a solution. A higher relative humidity as in practice has only negative effect no condensation. If the amount of vapour in the winter is more than 500g/m^2 than there should be a solution against the condensation. In this case the condensation in the summer is more than in winter and this means that the condensation is between the limitations. For security reasons a vapour barrier is recommended.

13) , 14), 15) and 16) The amount of vapour diffusion is between the limitations, according to the Glaser method.

5.5.8 Can condensation occur by the appliance of a vertical greening system?

After vapour diffusion calculations for bare wall and three vertical greening systems (green façade directly, green façade indirectly and LWS based on planter boxes) mentioned in paragraph 2.3.1 the effects of vertical greening systems are determined for applying the systems in practice. The summer measurements for the tested vertical greening systems show that condensation does not occur in any layer through the wall structure.

It became clear from the winter measurements that the tested vertical greening systems in winter cause condensation inside the wall structure. The condensation is occurred at all measured greening systems with freezing temperatures. It is important to notice that the relative humidity outdoor and indoor, vertical greening system type, outdoor and indoor temperatures play a role in determining of condensation and vapour diffusion. LWS based on planter boxes shows condensation in different layers (1-between LWS and outer surface of the wall; 2-between masonry and insulation material; table 5.13), while the direct and indirect greening systems with *Hedera helix* condensate only between two layers of the wall structure (between masonry and insulation material; table 5.11 and 5.12). But in all cases the limits of the amount of condensation according to Glaser method is not exceeded. For preventive reasons it is advised to use vapour barrier to prevent the moisture transport through the walls of the buildings with applying green on it. The movements of relative humidity through the wall structure during the measurements indoor to outdoor and vice versa are included in graphs which are added in annex B.

6 Sustainability and a life cycle analysis (LCA)

6.1 Introduction

When we think about vertical green and environment, we think actually about our current generation now and also the generations in the future. To build with vertical green, it is necessary to take in to account that manufacturing of supporting structures can have negative environmental effects. In this stage it is needed to know something about sustainability and durability and the term 'sustainable construction'.
Sustainable construction could be described as a way of designing and constructing building that support human health (physical, psychological and social) and which is in harmony with nature, both animate and inanimate. In case of sustainable construction the term 'sustainable' has two meanings in Dutch, i.e. durable and sustainable.

- Durable refers to the property of a material, building section or construction that can resist unacceptable deterioration of relevant functional characteristics through specific chemical, physical and mechanical loads, over a certain period of time (Hendriks, 2001).

- Sustainable refers to the general property of a material, building section or construction that indicates whether or not specific demands are met for affecting the air, water and soil qualities, for influencing the health and wellbeing of living organisms, for use of raw materials and energy, and even for scenic and spatial aspects, as well as for creating waste and nuisance (Dobbelsteen & Alberts, 2001; Hendriks, 2001).

6.2 Sustainability

At present we live in an age where "sustainability" is more appreciated than other trends such as quality, speed and production flexibility which dominated the last quarter-century (Sobrino et al., 2010). This new sustainability era is motivated primarily by social awareness in achieving a balance between human development and conservation of the environment. The term 'sustainability' was introduced in the Netherlands in the first National Environment Policy Plan (1989) and tries to adhere the term as mentioned in the UN report Our Common Future (Brundlandt). The NEPP describes sustainable development as follows: Sustainability is about living in a way that meets the needs and goals of people today, without affecting the ability of future generations to meet their own needs (Hendriks, 2001). In other words, sustainable development seeks to ensure a better quality of life for all both now and in the future. The capacity of biosphere can not indefinitely neutralise the consequences of human activity. Certain boundaries have been exceeded for a long time now. There is also an unequal distribution of the availability of this environment capacity, i.e. 20% of the world's population (obviously the industrialised countries) are responsible for almost 80% of the world wide energy consumption. Sustainable development would mean that specific environmental capacity boundaries must not be exceeded. As 'user' of the environment everyone is responsible for the way in which we use this environmental capacity. The so-called 'Factor 20' is a metaphor, a guideline for sustainable development and to make specific steps forwards. The metaphor can also be used for sustainable construction. Factor 20 refers to the aim (in 2040) to have the environmental impact per unit of prosperity reduced by a factor of 20, thus meeting social needs 20 times as environmentally efficiently, in this case building housing and other properties.

Sustainability is related to economy, society and environment (figure 6.1).

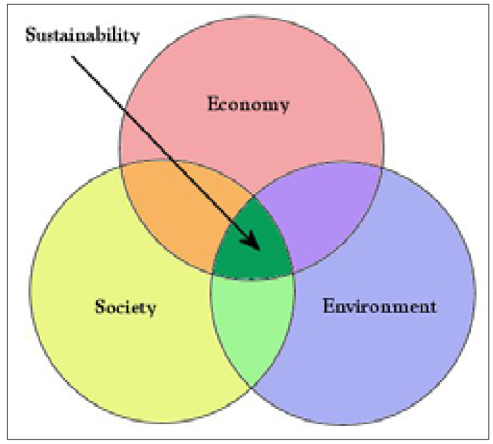


Figure 6.1: sustainability is related to economy, society and environment (source: www.melbourneuniversity.edu.au).

6.2.1 Background of sustainability

Before the concepts of sustainability were introduced, people built with checklists and preference lists as tools. With the introduction of the term sustainable building was a proliferation to these lists that were often based on personal preferences and incomplete information. To combat this proliferation, the SBR (Stichting Bouw Research) developed a general list, which is the national sustainable building package. This package was still looking into the practical side rather than on laws based scientific methods. The reason why sustainable building is encouraged is clear, but it should be qualified whether it is really a sustainable building. The most suitable method for this is the life cycle analysis (LCA). The life cycle analysis (LCA), is presented in 1992 by the CML (research centre), is a standardized scientific method for environmental assessments, which has received both national and international recognition. (Dobbelsteen & Alberts, 2001).

6.3 The Life Cycle Analysis (LCA) and its application

The life cycle analysis (LCA) methodology examines the overall environmental impact of a product throughout its entire lifecycle. All materials and energetic inputs and outputs are examined, such as the necessary raw materials, production, transportation, use and disposal (figure 6.2). The LCA is also called the cradle to grave approach because it is not only assumed to the environmental impacts of the material during the construction and use phase, but the whole range of extraction, transportation, processing, recycling and waste is also included (Hendriks et al., 2000).

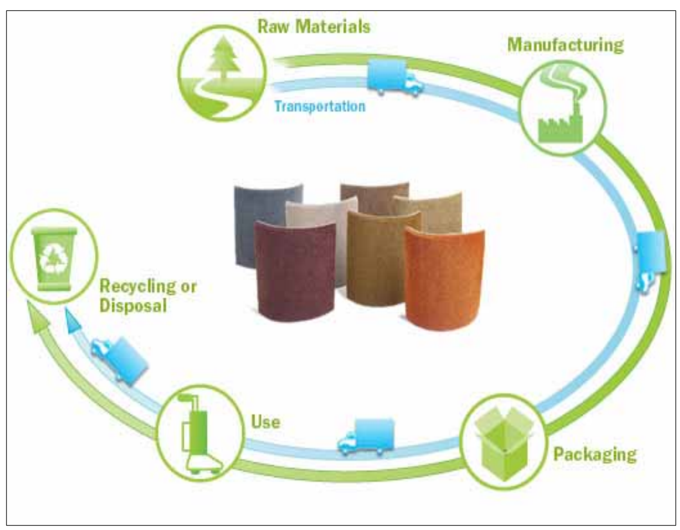


Figure 6.2: LCA cycles (source: www.interfaceglobal.com).

The LCA aims to record the use of raw materials and to point out possible environmental problems during the demolition, recycling and second life cycle of construction products. The result is a profile of raw materials and an environmental profile based on quantities used and a scoring (points) system. The LCA is more a quantitative data and if these data are missing, than we use the qualitative aspects to have a complete overview of it. The LCA can be applied in four steps to design a complete process.

1- Goal, scope and definition
2- Inventory Analysis
3- Impact Assessment
4- Interpretation

Step 1: Goal and scope definition
In this step the objectives will be determined for the setting up of the functional unit. The LCA gives environmental information that can be used for:

- product comparison;
- product testing;
- product and process improvement and innovation;
- steering of policy strategies;
- market operation.

Each of these objectives corresponds to a certain target group. Thus the building column represents designers and clients, who must choose from the raw materials and semi-manufactured products on offer. Improvement and innovation are important for suppliers and manufacturers.

The next step in determining of the objectives is to choose a functional unit. Determining functional unit and process tree, herewith the comparison can be set for the alternative. The functional unit describes which functions the products or item in certain periods must perform and which processes are required. It is also here important to know what belongs to a process and there will be looking to the recycling. A product function offers better base for comparison than product as such.

Step 2: inventory analysis (functional unit and product choice)
In this step, a list or table will be made to note all of environmental aspects of the products during the product life cycle. It is usually mainly the emission of pollutants and the use of fuel and raw materials. Also things like land use, noise and stink are discussed by inventory analysis. The main point is to find how human can intervenes the environment and therefore it is called environmental intervention.

Step 3: impact assessment
This step involves a selection of environmental effect, allocation of emissions to environmental effects, determining score for environmental effects, normalization of score and the eventual weighting of the environmental effects.

Step 4: interpretation (evaluation)
Interpretation involves the analysis of environmental effects and some determined factors to mention the influence of assumptions and principles. In this stage you can see which interference has the big contribution for environment and after that, the environmental profile will be compared with the research question. Evaluation, with the normalized environmental profile is possible to compare variants and with an overall weighting score would be formed.

6.4 Life cycle analysis for vertical greening systems

6.4.1 Description of the used vertical greening systems

As it is already mentioned in chapter 2.3, the following vertical greening systems are measured in the hotbox for their insulating character as a part of the PhD project (Ottelé, 2011).

1. bare wall (without any green surface) as a basic for all the measurements

Green façades

2. a wall with self climbing plants (*Hedera helix*, directly to the wall)
3. a wall with self climbing plants on supporting structure (*Hedera helix*, indirectly to the wall)

Living wall systems (LWS)

4. planter boxes (Greenwavesystem)
5. felt layers system (Wonderwall of copijn)
6. **mineral wool based system (Wallflore, cultilene)**
7. **foam based system (Fytowall- fytogreen)**

From the list above (1 up to 5) are analysed as a part of the PhD project of "The green building envelope" (Ottelé, 2011). In this graduation project, only two living wall systems (6 and 7) will be taken in to account for the life cycle analysis as discussed in paragraph 2.3. The goal is to determine the impact of the raw material depletion, fabrication, transportation, installation, operation, maintenance and waste for two greening systems compared to a bare façade.

6.4.2 Functional unit

A particularly important issue in product comparisons is the functional unit or comparison basis. According to ISO 14040, "the functional unit is a measure of the function of the studied system". The functional unit should be defined so that the different greening systems being compared provide the same services, for a similar duration.

In this stage the vertical greening alternatives will be compared with a bare wall. The functional unit for this LCA will be performed for 1 m^2 wall including all layers and materials. The LCA performance for 1 m^2 is done as a basis of a fictitious surface (façade) of 100 m^2 based on (Ottelé et al., 2011). The presented LCA research examines two living wall systems applied on a façade to compare the environmental burden and benefits of the vertical greening systems with a bare wall (brick masonry).

1) a façade covered with a living wall system based on mineral wool (bare wall + vegetated mineral wool panels)
2) a façade covered with a living wall system based on foam substrate (bare wall + vegetated foam boxes).

The transported distances are from providers (companies) to Delft city. The distance from mineral wool based company to Delft is 70 km and for the LWS based on foam substrate the distance is 105 km (table 6.2b and c). Figure 6.3 shows the layers of the bare wall (as basis for the vertical greening systems comparison) which is constructed by lime stone, insulation material, air cavity and masonry.

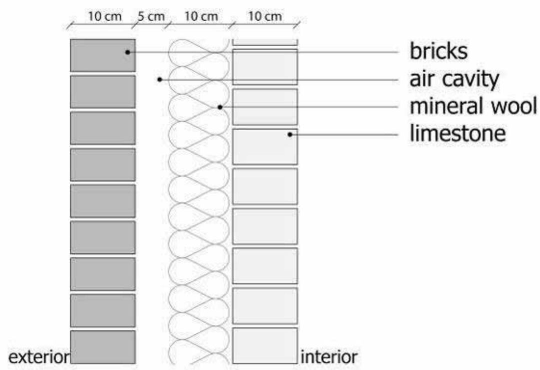


Figure 6.3: Bare wall with materials layers (source: Ottelé et al., 2011).

1) The first investigated greened façade, is a living wall system (figure 6.4), based on mineral wool and planted with evergreen species (*Pteropsida*), working with a system for water and nutrients. The system consists of bare wall + air cavity + mineral wool + vegetations.

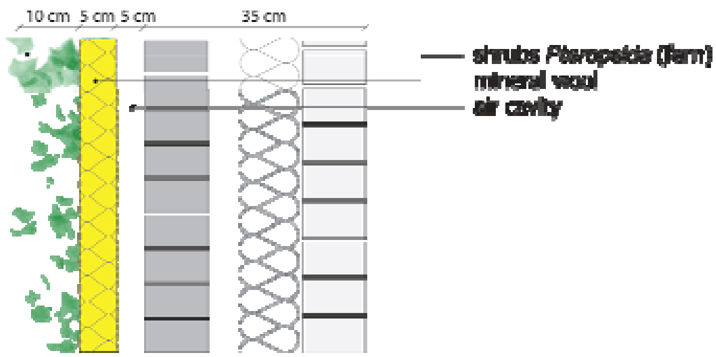


Figure 6.4: LWS based on mineral wool with materials layers.

2) The second vertical greening system (figure 6.5) is a living wall system based on foam substrate and planted as well with ferns (*Pteropsida*) and working with a system for water and nutrients. The system consists of bare wall + air cavity + foam boxes + vegetations.

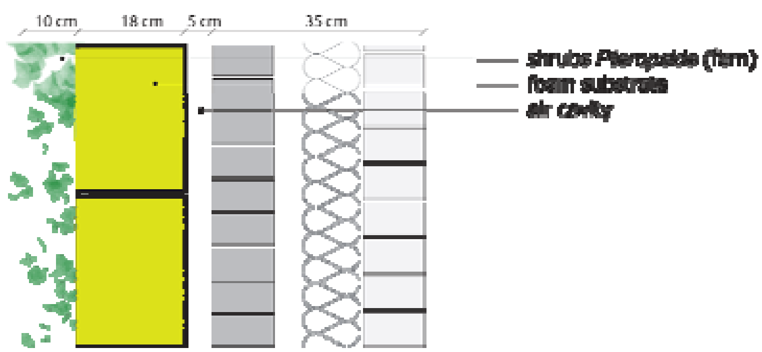


Figure 6.5: LWS based on foam substrate with materials layers.

The results of the LCA are noted as the accumulation of environmental impact over the service life. Therefore the frequency of maintenance activity and the times at which replacements are needed are described. At the end the assumptions and limitations of life cycle analysis and the data will be discussed.

6.4.3 Tools

The database used to develop the process models for this analysis is based on the Dutch National Environmental database compiled by the Dutch Institute for Building Biology and Ecology (NIBE). The complete set of environmental impact categories is known as the "environmental profile". The environmental profile is divided in ten categories (Ottelé, 2011):

1- abiotic depletion (kg Sb equivalents)
2- global warming (kg CO_2 equivalents)
3- ozone layer depletion (kgCFC-11 equivalents)
4- human toxicity (kg1.4-DB equivalents)
5- fresh water aquatic ecotoxicity (kg1.4-DB equivalents)
6- marine water aquatic ecotoxicity (kg1.4-DB equivalents)
7- terrestrial ecotoxicity (kg1.4-DB equivalents)
8- photochemical oxidation (kg C_2H_4)
9- acidification (kg SO_2 equivalents)
10- eutrophication (kg PO_4 equivalents)

Category 6 (marine water aquatic ecotoxicity) will not be taken into account because of considerable problems associated with the calculation of the impact in the method. These problems are related to the time a substance is present in the marine ecosystem and missing data for normalization (Blom et al. 2010). The environmental calculation is built up by three main classes: materials, transportation and waste. For every class the environmental burden is calculated according to the ten categories described above.

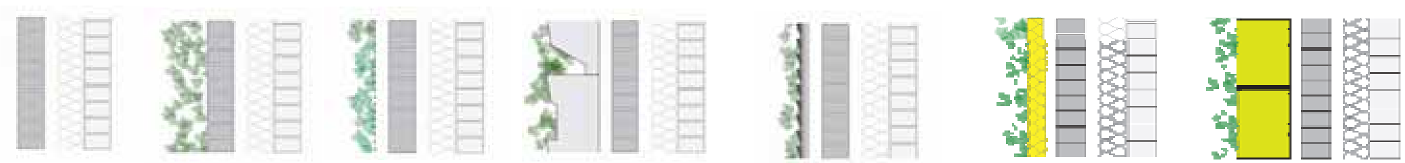
6.4.4 Data inventory

Table 6.1 shows the components and materials for bare wall and six vertical greening systems. The green marked systems (1 up to 5 in table 6.1) are already done by Ottelé et al., (2011). As it is already mentioned in this report only two systems (6 and 7 in table 6.1) are added and will be analyzed.

Bare wall components are listed in the table below as the basis for all vertical greening systems. The greening systems make the difference between the bare wall and the applied systems. The layer added by LWS number 6 is based on mineral wool and the layer added by LWS number 7 is based on foam substrate. The materials details are obtained from product information forms which are given by companies.

Table 6.1: components and materials for bare wall and green system analyzed and based on Ottelé et al. 2011.

components	**1. bare wall**	**2. direct green**	**3. indirect green**	**4. LWS planter boxes**	**5. LWS felt layers**	**6. LWS mineral wool**	**7. LWS foam substrate**
inner masonry	lime stone	lime stone	lime stone	lime stone	lime stone	lime stone	lime stone
Insulation material (mineral wool)	100 mm	100 mm	100 mm	100 mm	100 mm	100 mm	100 mm
air cavity	50 mm	50 mm	50 mm	50 mm	50 mm	50 mm	50 mm
Outer masonry	brick (clay)	brick (clay)	brick (clay)	brick (clay)	brick (clay)	brick (clay)	brick (clay)
air cavity	---	---	50 mm	50 mm	50 mm	50 mm	50 mm
structural support	---	---	steel mesh	steel profile	steel profile	steel profile	steel profile
supporting system	---	---	---	HDPE boxes	PVC foam plate	aluminium	PE basket
inner layer	---	---	---	---	white fleece	---	---
growing material	---	terrestial soil	terrestial soil	potting soil	wool fleece	mineral wool	aminoplast
damp open foil	---	---	---	---	PE fleece	---	---
outer felt layer	---	---	---	---	black fleece	black fleece	black fleece
irrigation system	---	---	---	PE pipes	PE pipes	PE pipes	PE pipes
water demand	---	groundwater	groundwater	tapwater + nutrients	tapwater + nutrients	tapwater + nutrients	tapwater + nutrients
vegetation	---	*Hedera helix*	*Hedera helix*	*Pteropsida* (ferns)	*Pteropsida* (ferns)	*Pteropsida* (ferns)	*Pteropsida* (ferns)



6.4.5 Assumptions

The service life for the analysis is assumed for a period of 50 years to study the environmental aspects and potential impacts for a façade. The life expectancy of the conventional bare wall is assumed to be 50 years as well as for the façades covered directly and indirectly with climbing plants (Dunnett and Kingsbury, 2004). The replacement frequencies of vegetations (plants) for living wall systems are assumed as 3.5 years for both mineral wool based system and foam based system. Per year 10% of plants will be replaced related to natural dying and demolition. The life expectancy for the aluminium frame of mineral wool panels is also expected 50 years as the life of façade. The life expectancy for black fleece is about 10 years and the life expectancy for mineral wool and foam substrate are not known yet, because the systems do not exist for a long time. When the black fleece should be changed, that means that the whole panel should be replaced. It is impossible to replace only black fleece because when the panels are fully grown, the roots will totally capture the panels or boxes. Therefore the whole module is assumed with a life expectancy of 10 years as well for both mineral wool based system and foam substrate based system.

The irrigation system used for living wall systems (mineral wool and foam based substrate) have to be replaced every 7.5 years because of crystallizing of salts. The amount of water and nutrients needed for the LWS is controlled by a self-automated system (due to the complexity of these systems), is not included in this analysis. Living wall systems need nutrient besides the irrigation system, which is not taken into account, due to the small (1%) influence (Ottelé, 2011). The water consumption for the living wall system based on mineral wool is assumed as a quantity of 2 litre/day (average value for whole year) and for the living wall system based on foam substrate 1 litre/day (average value for whole year), (tables 6.2a-b-c).

For both the greening systems analyzed in this graduation project the possibility of recycling and reuse is taken into account. If it is possible, for the waste class, the option recycling or reuse is chosen for the calculation. Exceptions are made if it is not possible to separate multiple layered components for recycling processes. In this case, due to the service life and complexity, none of the materials will be reused.

Table 6.2a: bare wall material weight (kg), transportation (km) and service life (y) of components.

1.Bare wall

components	material	weight (kg/m^2)	distances (km)	service life (years)
inner masonry	limestone	147	62	50
insulation	mineral wool	4,3	190	50
air cavity	cavity	---	---	---
outer masonry	brick (clay)	145	80	50
mortar	sand+cement+water	84	15	50

Table 6.2b: LWS based on mineral wool, material weight (kg), transportation (km) and service life (y) of components.

6*.LWS mineral wool

components	material	weight (kg/m^2)	distances (km)	service life (years)
inner masonry	limestone	147	62	50
insulation	mineral wool	4,3	190	50
air cavity	cavity	---	---	---
outer masonry	brick (clay)	145	80	50
mortar	sand+cement+water	84	15	50
bolts	steel S235	0,13	70	---
spacer brackets	steel S235	0,19	70	---
air cavity	cavity	---	---	---
supporting U section	steel S235	4,62	70	---
Aluminium frame	aluminium	2.9	70	50
Mineral wool	Rockwool	4,3	70	10
black fleece	Polypropylene	0,85	70	10
vegetation	*Pteropsida*	7,5	30	3,5
watering system	PE	0,09	35	7,5
Water demand	tap water	730	0	1

Table 6.2c: LWS based on foam substrate, material weight (kg), transportation (km) and service life (y) of components.

7*.LWS foam based

components	material	weight (kg/m^2)	distances (km)	service life (years)
inner masonry	limestone	147	62	50
insulation	mineral wool	4,3	190	50
air cavity	cavity	---	---	---
outer masonry	brick (clay)	145	80	50
mortar	sand+cement+water	84	15	50
bolts	steel S235	0,13	105	---
spacer brackets	steel S235	0,19	105	---
air cavity	cavity	---	---	---
supporting U section	steel S235	4,62	105	---
planter basket	PE	7,66	105	10
Foam substrate	aminoplast	0,3	105	10
black fleece	Polypropylene	0,43	105	10
vegetation	*Pteropsida*	7,5	30	3,5
watering system	PE	0,09	35	7,5
Water demand	tap water	365	0	1

6.4.6 Interpretation and analysis of results

Environmental burden analysis

After performing a LCA for mineral wool based living wall system and foam based living wall system the results will be discussed. Three environmental profiles (global warming, human toxicity and fresh water aquatic ecotoxicity) are considered for showing the results due to the very small (almost zero) influence of the other six categories. The results show that there is a substantial difference between the greening systems and the bare wall, except for the direct

* Number 6 corresponds with continuation of the data inventory for vertical greening systems based on Ottelé et al. (2011).

greening system. This shows that the supporting structures make the main difference. Figure 6.6 shows that the global warming contribution of mineral wool and foam substrate are with a small difference and less than living wall system based on felt layers. But it is possible o deduce for global warming that the living wall system based on felt layers is more than double compared to the other greening systems.

For the human toxicity the living wall system based on mineral wool has a high impact compared to the bare wall, the direct greening system and other greening systems. For the fresh water aquatic ecotoxicity, the living wall system based on felt layer has the highest impact end after that the living wall system based on mineral wool has the second degree. Living wall system based on foam substrate has more or less the same impact as indirect greening. The environmental burden for stainless steel in the database is based on 30% of recycled stainless for the production process. This percentage is a common average used in databases worldwide, but the amount of recycled stainless steel could be higher which could lead eventually to a lower environmental burden.

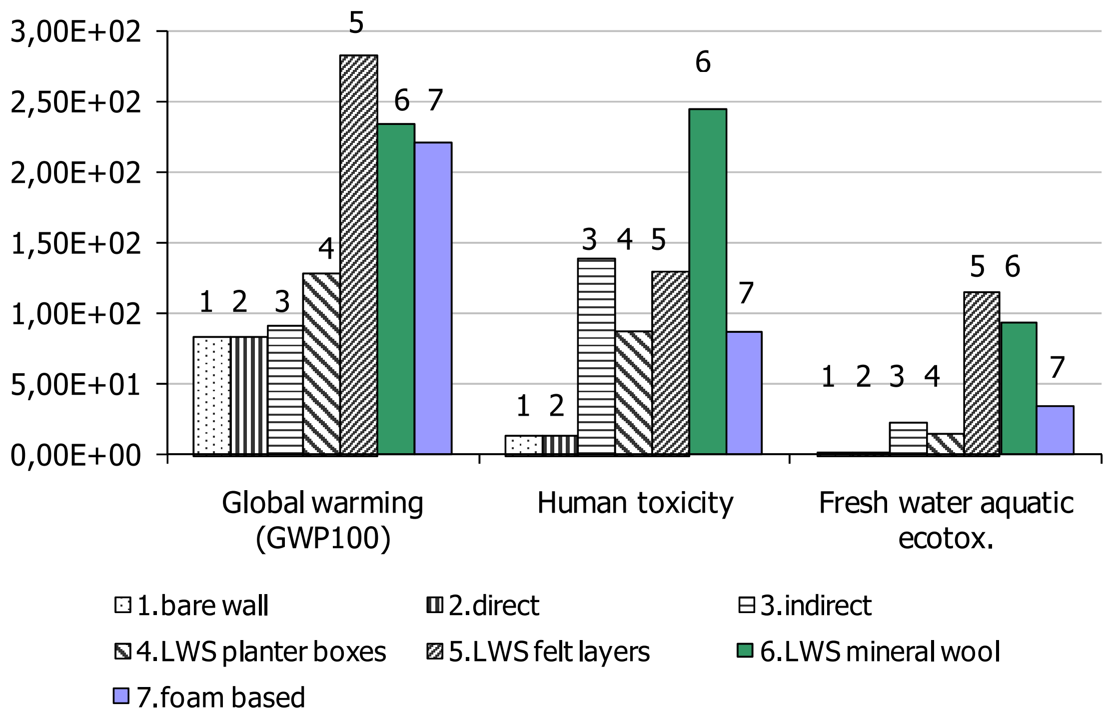


Figure 6.6: environmental burden profile for global warming, human toxicity and freshwater aquatic ecotoxicity, given for all six greening systems. This is based on a functional unit of 1m^2.

The graph in figure 6.7 made for mineral wool based living wall system and the graph in figure 6.8 made for foam based living wall system show the influence for the classes material, transportation and waste of the bare wall, supporting systems and vegetation. The highest difference found in the analysis regards the material impact for the supporting systems. This relates to the impact of the production of aluminium frame of mineral wool based living wall system. Foam based living wall system has a lower environmental burden than the mineral wool based living wall system, which relates to use of planter baskets (PE). The impact of the vegetation is almost the same for both named living wall systems.

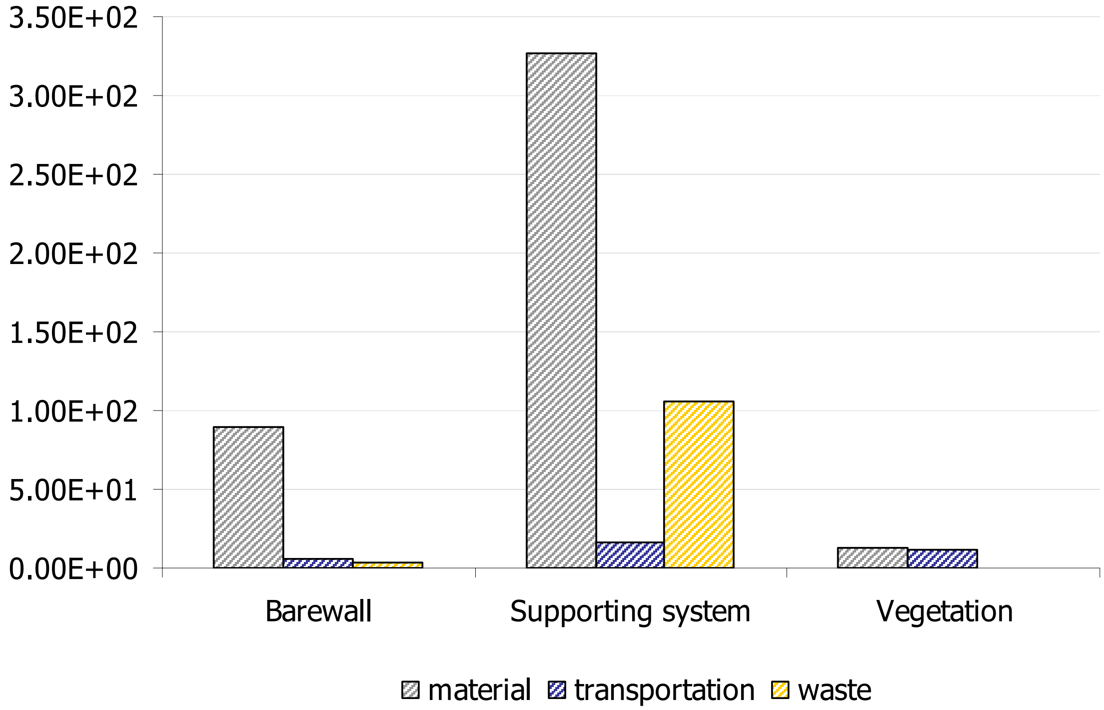


Figure 6.7: total environmental burden profile for classes material, transportation and waste for LWS based on mineral wool. This is based on a functional unit of 1m².

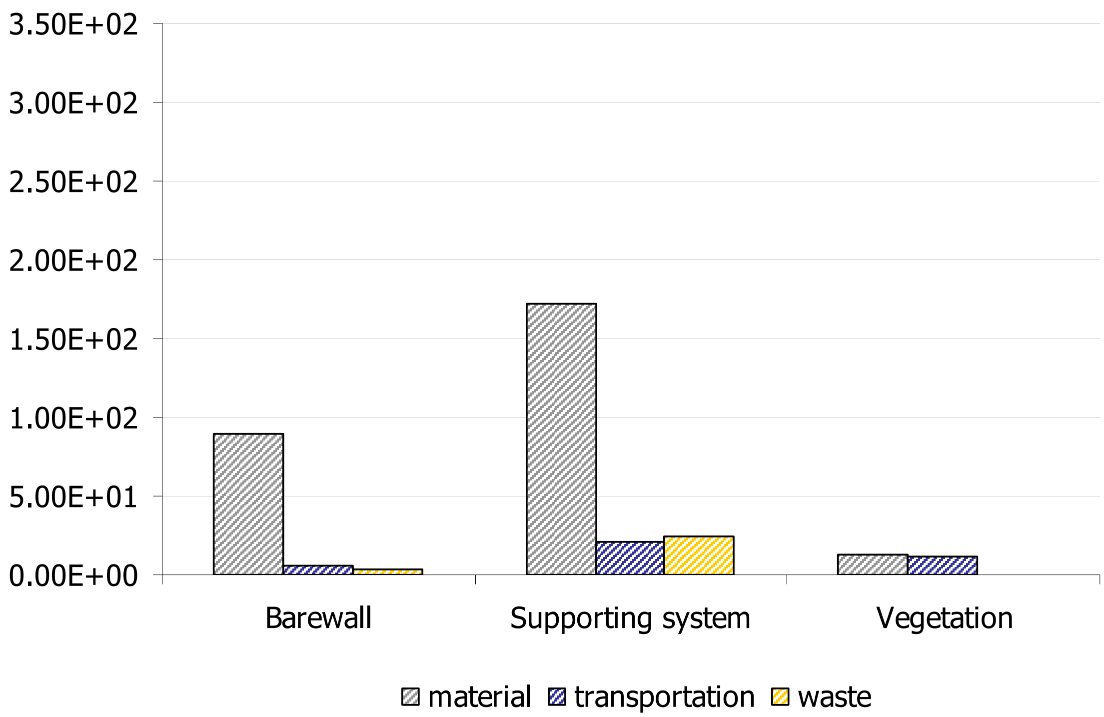


Figure 6.8: total environmental burden profile for classes material, transportation and waste for LWS based on foam. This is based on a functional unit of 1m².

Environmental benefits analysis
Global warming, human toxicity and fresh water aquatic ecotoxicity are again the profiles which are related to the environmental benefits as for environmental burdens. These categories are related to energy saving for heating and air conditioning.

Figures 6.9 shows the environmental benefits profile for Mediterranean climate. From figure 6.9 it can be derived that the benefits for heating for the living wall systems are more than two times the direct and indirect greening system. Living wall system based on mineral wool and living wall based on foam substrate have more or less the same values. This is mainly caused by the contribution for the insulation properties of the materials involved. The difference between living wall systems and both direct and indirect greening systems is that the direct and indirect greening systems have only vegetation as insulation, while the living wall systems have more layers beside the vegetations for the insulating properties. The difference between the living wall systems is very small compared to direct and indirect greening systems. Soil package of planter boxes and mineral wool have clearly a little bit higher insulating property than foam based substrate and felt layers.

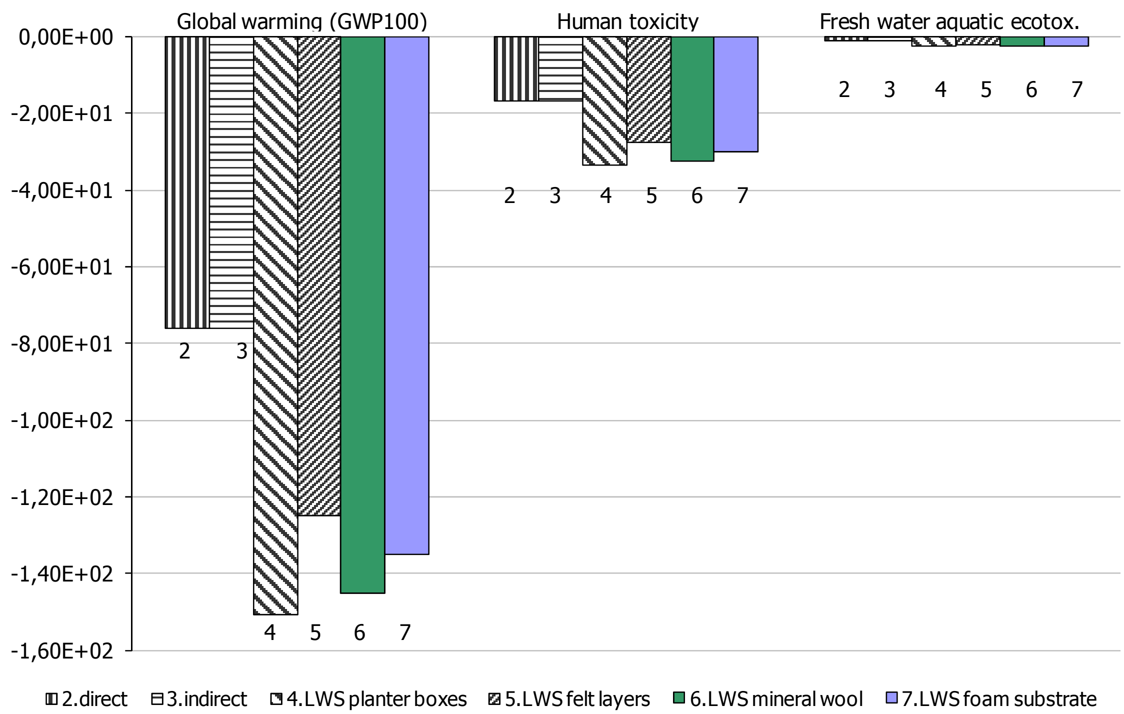


Figure 6.9: environmental benefits profile (heating and cooling) for Mediterranean climate given for global warming, human toxicity and fresh water aquatic ecotoxicity, given for all six greening systems. This is based on a functional unit of 1m².

Figures 6.10 shows the environmental benefits profile for temperate climate. From figure 6.10 it can be derived that the benefits for heating for the living wall systems are more than three times the direct and indirect greening system. Living wall system based on mineral wool and living wall based on foam substrate have a small difference compared to direct and indirect greening systems. This is mainly caused by the contribution for the insulation properties of the materials involved the same as for Mediterranean climate. The difference between living wall systems and both direct and indirect greening systems is that the direct and indirect greening systems have only vegetation as insulation, while the living wall systems have more layers beside the vegetations for the insulating properties. The difference between the living wall systems is not too large compared to direct and indirect greening systems. Soil package of planter boxes and mineral wool have clearly a little bit higher insulating property than foam based substrate and felt layers. As it is clear on figure 6.10 living wall system based on felt layers have the lowest insulating property compared to other living wall systems.

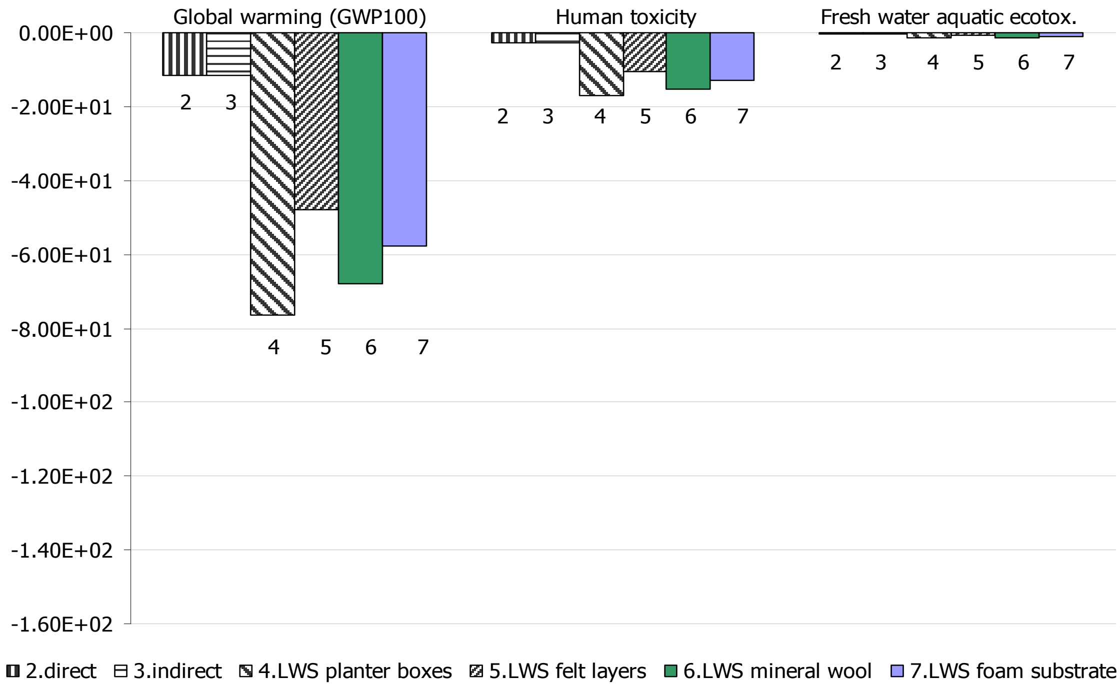


Figure 6.10: environmental benefits profile (heating) for temperate climate given for global warming, human toxicity and fresh water aquatic ecotoxicity, given for all six greening systems. This is based on a functional unit of 1m².

Overview of environmental burdens and benefits

The life cycle analysis presented in this chapter shows the difference between the vertical greening systems and a bare wall analyzed for the environmental burden and for the environmental benefits related to Mediterranean climate and temperate climate. The transported distances (in the Netherlands) are included in the calculated environmental burden profile. The results about the environmental burden of this study could be projected also to other locations, since the transportation distances could be similar for example in Europe (all the materials in this analysis are commonly available).

The environmental burden profiles show that the analyzed living wall systems have a major impact (due to the materials used and the life span). The environmental profile can be reduced by more sustainable material choice and an integrated envelope design. The environmental burden profile for the living wall system based on mineral wool appears to be almost the same with living wall system based on foam substrate since the aluminium panels of mineral wool based LWS play an important role. In general both LWS based on mineral wool and LWS based on foam substrate have almost the same contribution to the energy savings for heating but, for the Mediterranean climate, a higher influence was noted for the cooling properties of the plants. The materials involved for the living wall system based on planter boxes affect the insulation properties and cause the highest energy saving for heating. After LWS based on planter boxes, the LWS based on mineral wool has the second grade and at third grade the LWS based on foam substrate has energy saving character for heating.

A system is sustainable when the environmental burden is lower than the environmental benefit profile (figure 6.11). For the temperate climate the environmental burden profile is higher than the energy savings for heating for all the greening systems (supporting system + vegetation), except for the direct greening system that is sustainable. For the Mediterranean climate, thanks to the energy savings related to air conditioning, the direct greening system is sustainable and also the living wall system based on planter boxes (column 4 on the graph in figure 6.11) is almost sustainable. For the living wall system based on felt layers, living wall system based on mineral wool and living wall system based on foam substrate in both climate types the environmental burden profile is higher than the benefits gained for heating and cooling. The benefits for heating and cooling and the environmental burden are both calculated for the service life of the vertical greening systems studied.

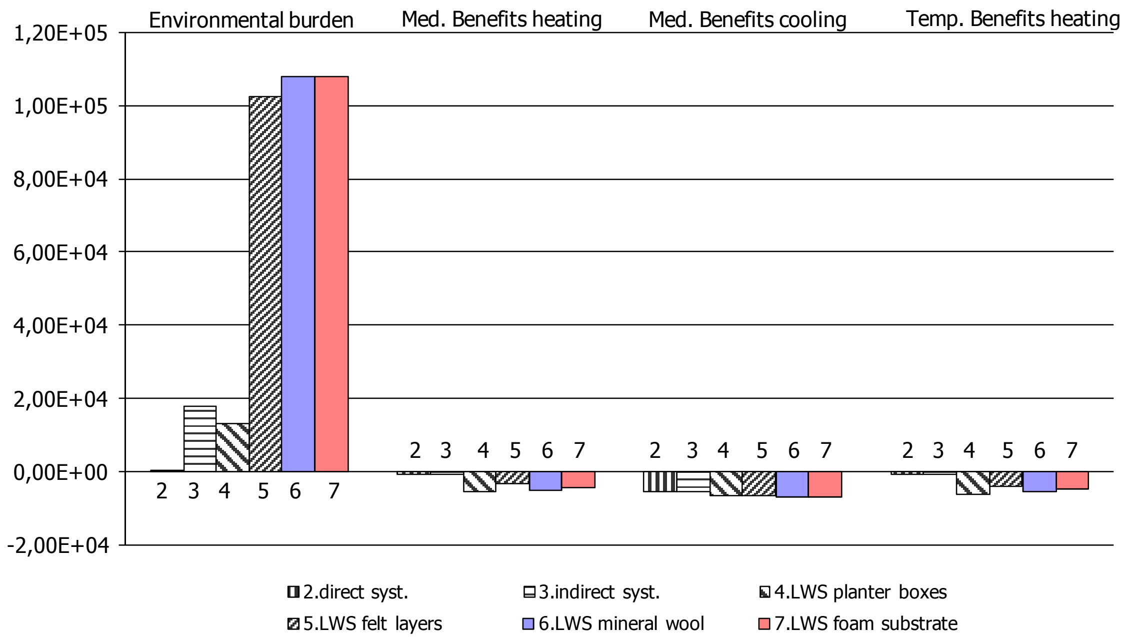


Figure 6.11: environmental burden for the six greening systems (supporting system + vegetation), benefits for heating and cooling for Mediterranean climate and benefits for heating for temperate climate. This is based on a functional unit of 1m².

7 Decision tree

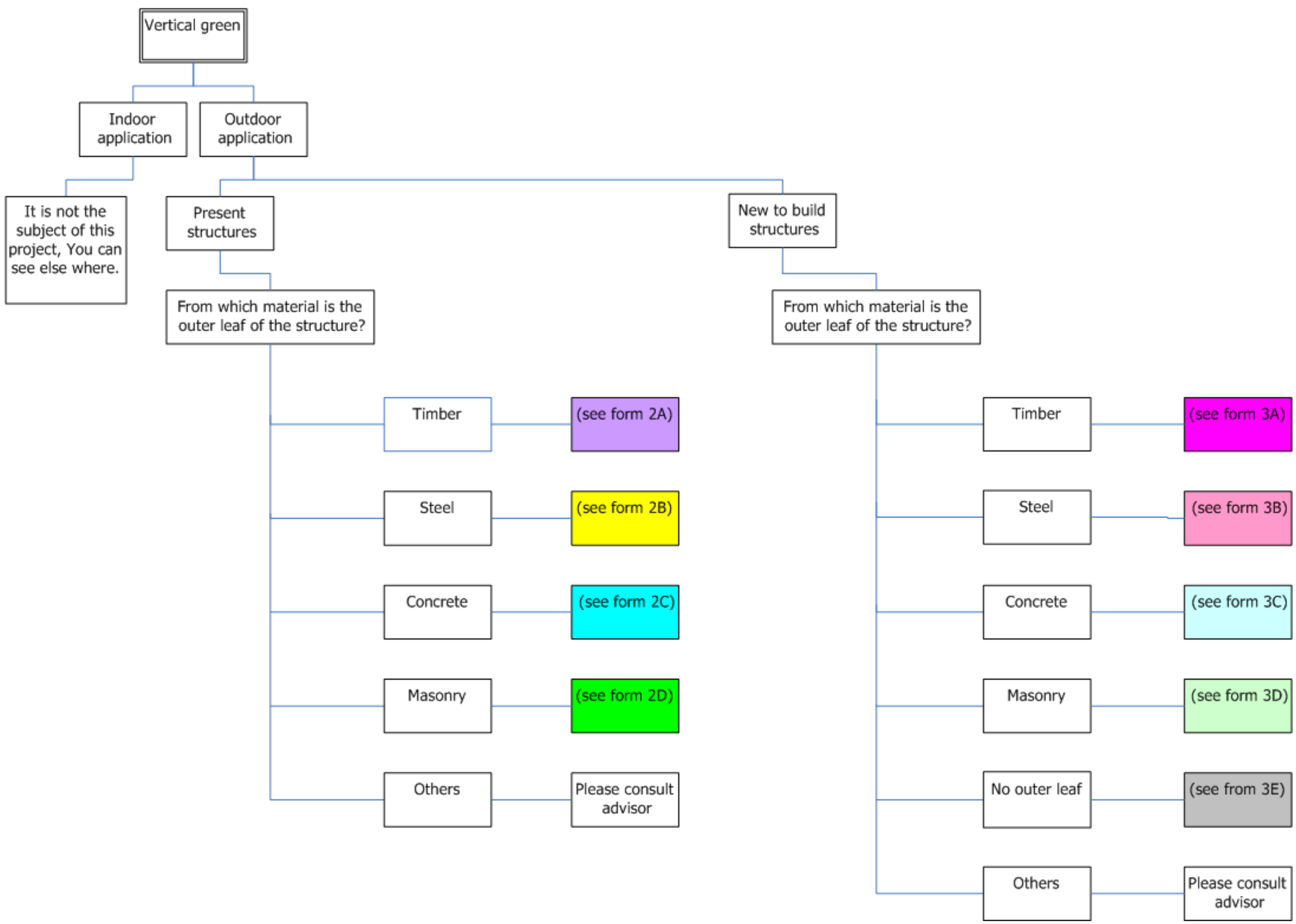
7.1 Introduction

After studying several vertical greening systems and their application forms, it is necessary to know which system in which condition can be used. In addition, it is interesting to know which combinations of materials and vertical greening systems could be possible for applying of vertical greening systems with respect to different buildings (such as present buildings, new to build buildings, old buildings and civil engineering structures such as noise barriers etc.). This chapter deals with a decision tree based on information and knowledge from literature and can lead to a well advised vertical greening decision.

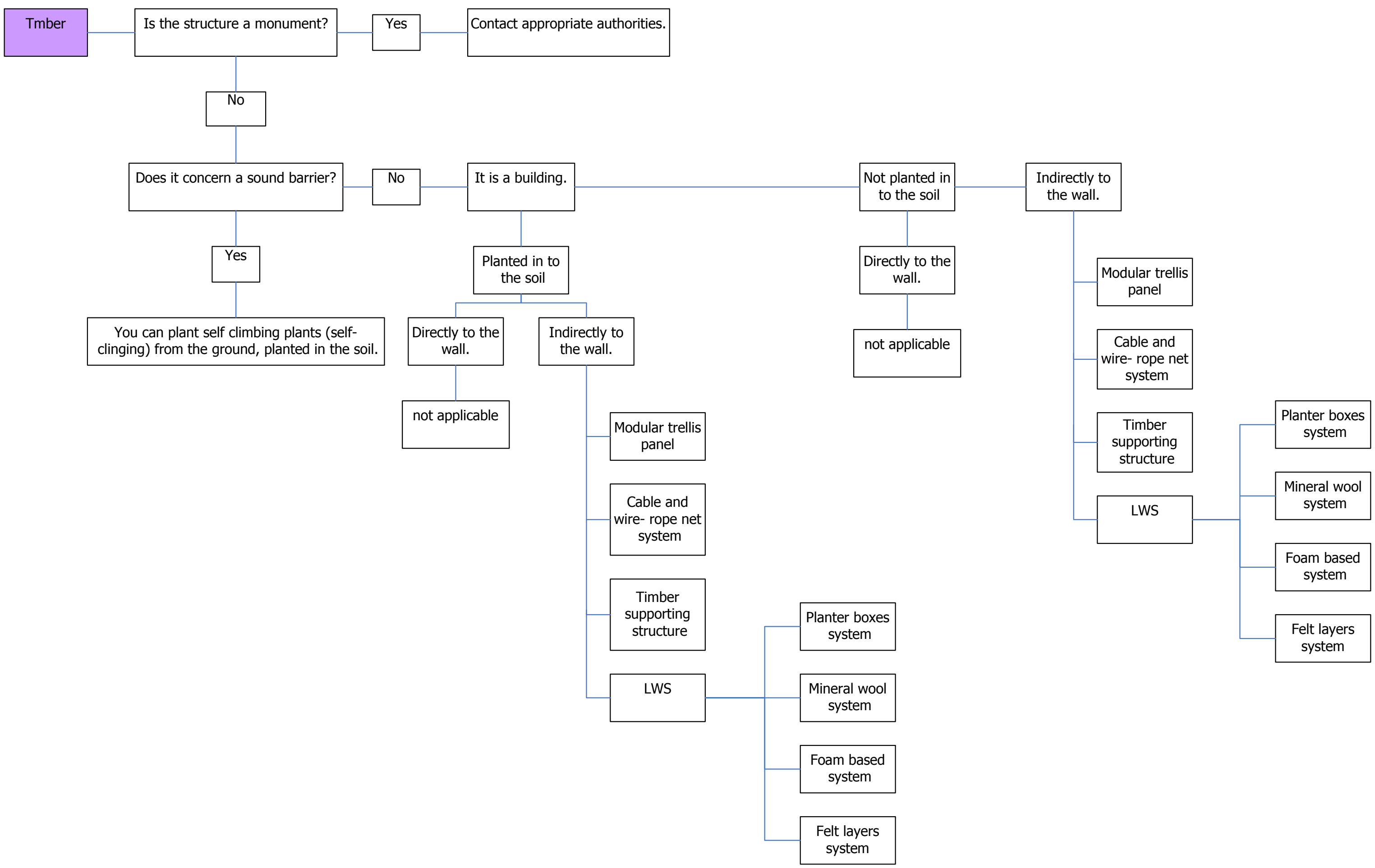
7.2 Decision tree about vertical greening systems

Decision trees are excellent tools for helping you to choose between several vertical greening systems. They provide a highly effective structure within which you can lay out options and investigate the possible outcomes of choosing a specific greening system, the output can be a yes/no decision. Several branches may extend from a single point, representing several different alternative choices or outcomes of vertical greening systems.

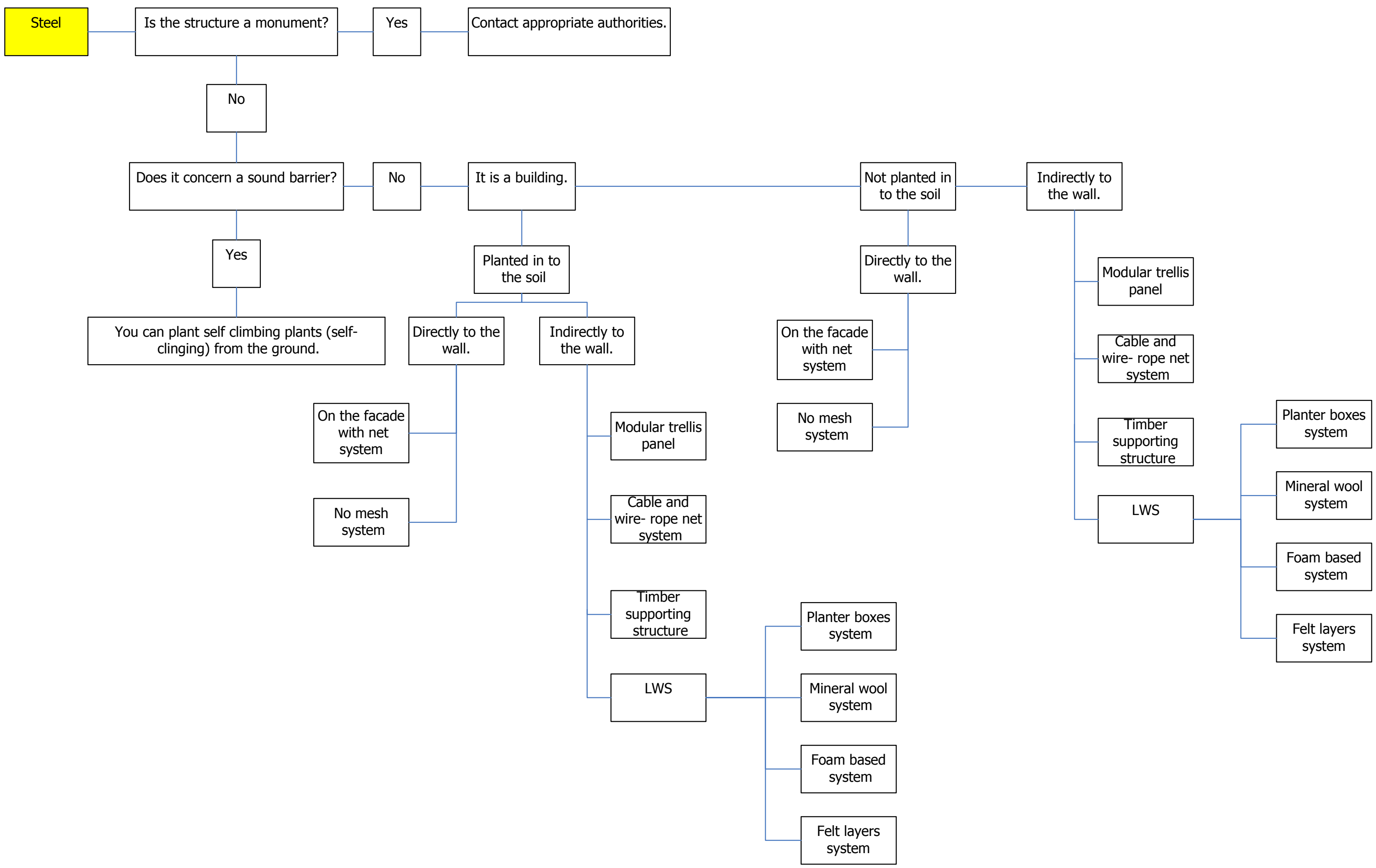
You start the following decision tree with a decision that you need to make about your choice. Inside the tree, construction type (existing or new to built) and material choice are the main paths to follow. According to these choices you can end with optimal vertical green system(s) to use on the structure.

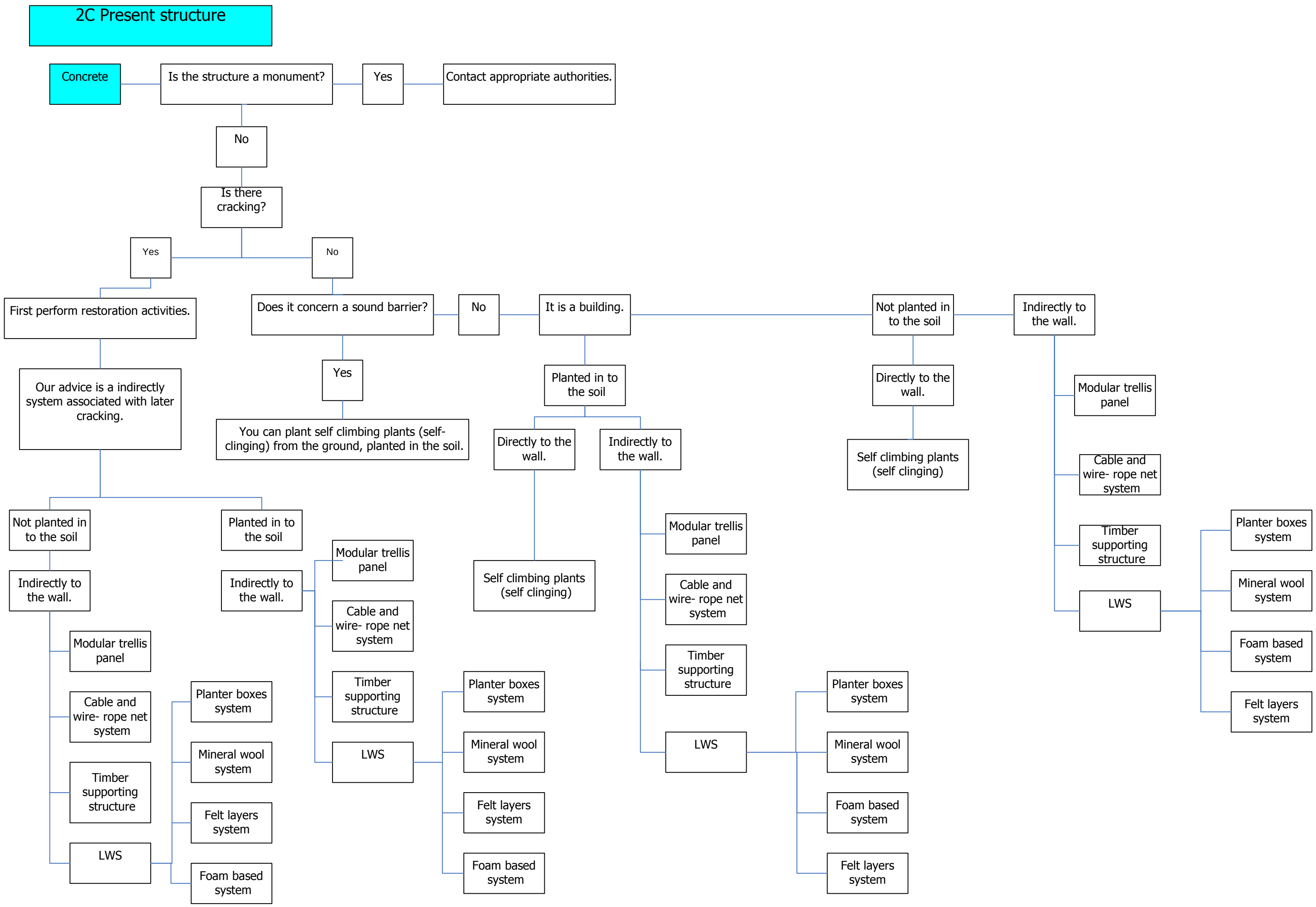

Vertical green
Indoor application
Outdoor application
It is not the subject of this project, You can see else where.
Present structures
New to build structures
From which material is the outer leaf of the structure?
From which material is the outer leaf of the structure?
Timber
(see form 2A)
Steel
(see form 2B)
Concrete
(see form 2C)
Masonry
(see form 2D)
Others
Please consult advisor
Timber
(see form 3A)
Steel
(see form 3B)
Concrete
(see form 3C)
Masonry
(see form 3D)
No outer leaf
(see from 3E)
Others
Please consult advisor

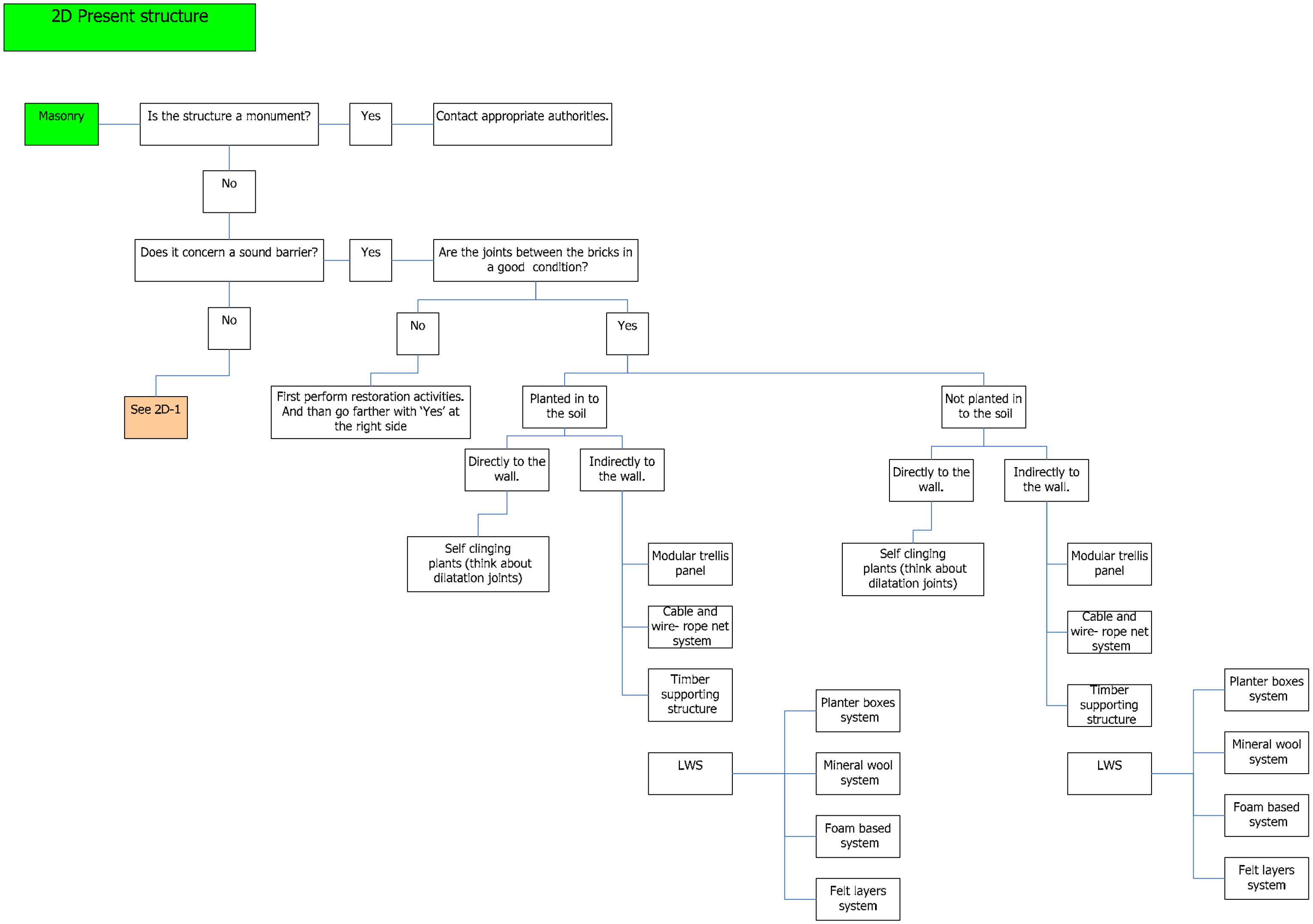
2A Present structure

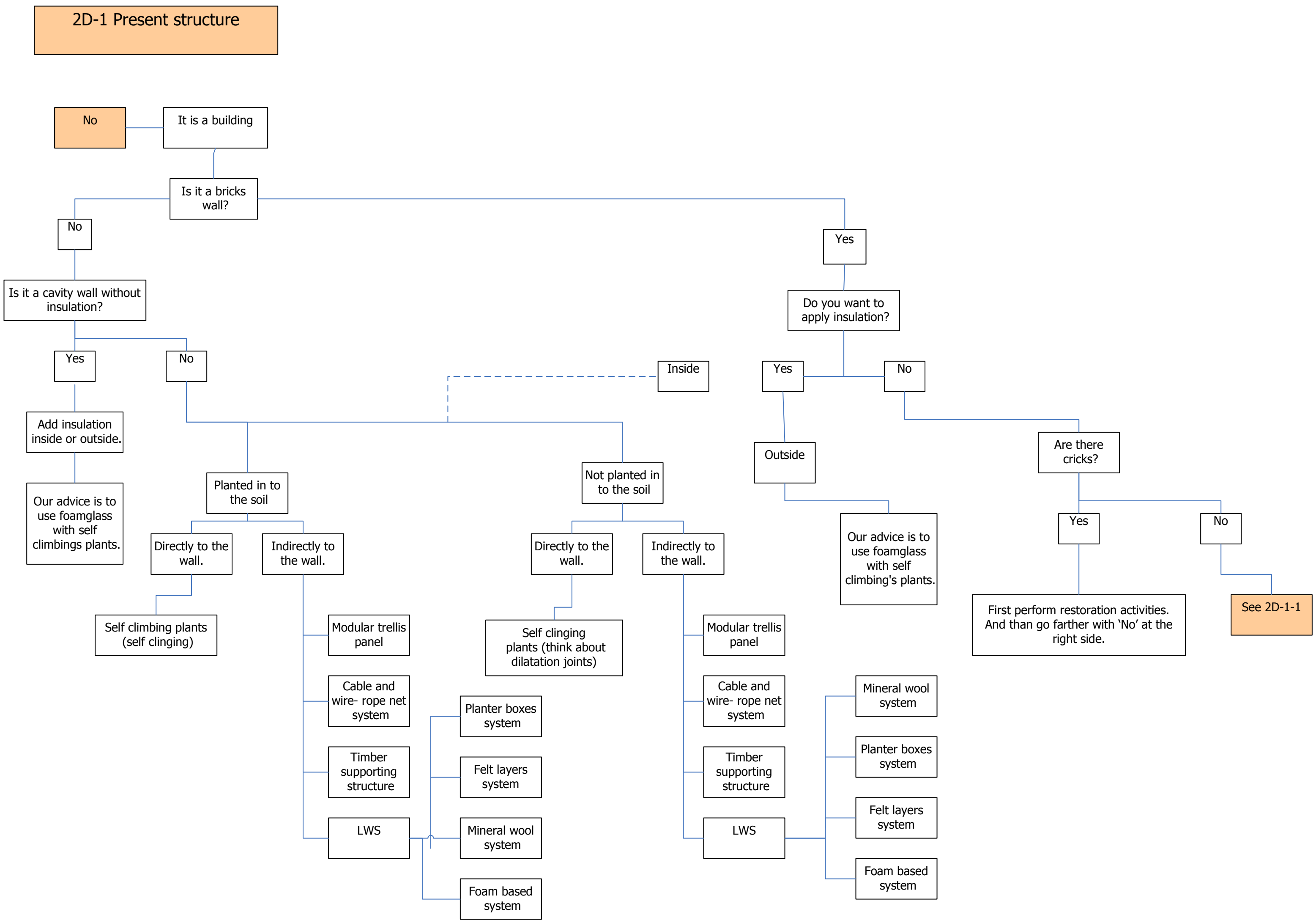


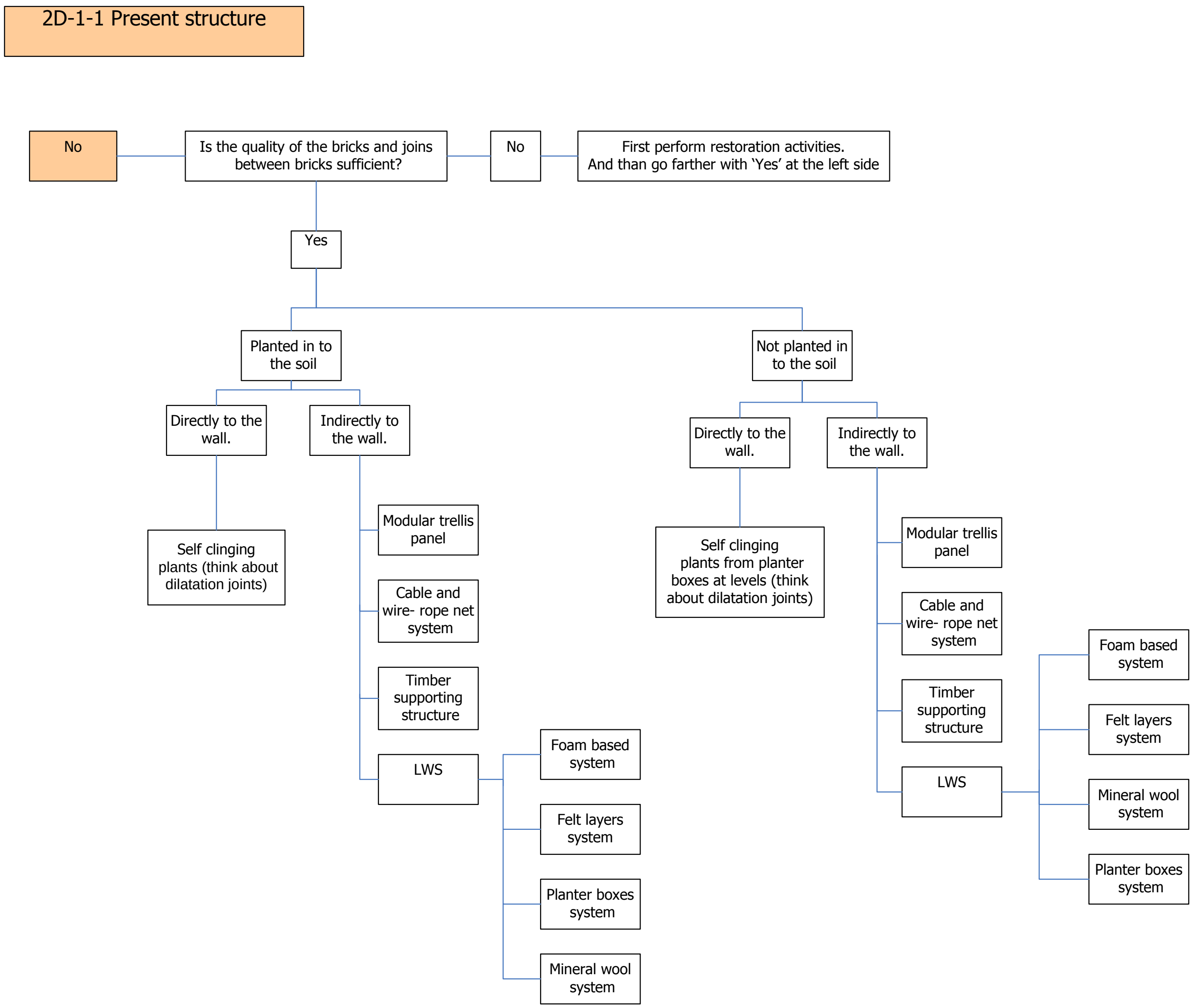
2B Present structure



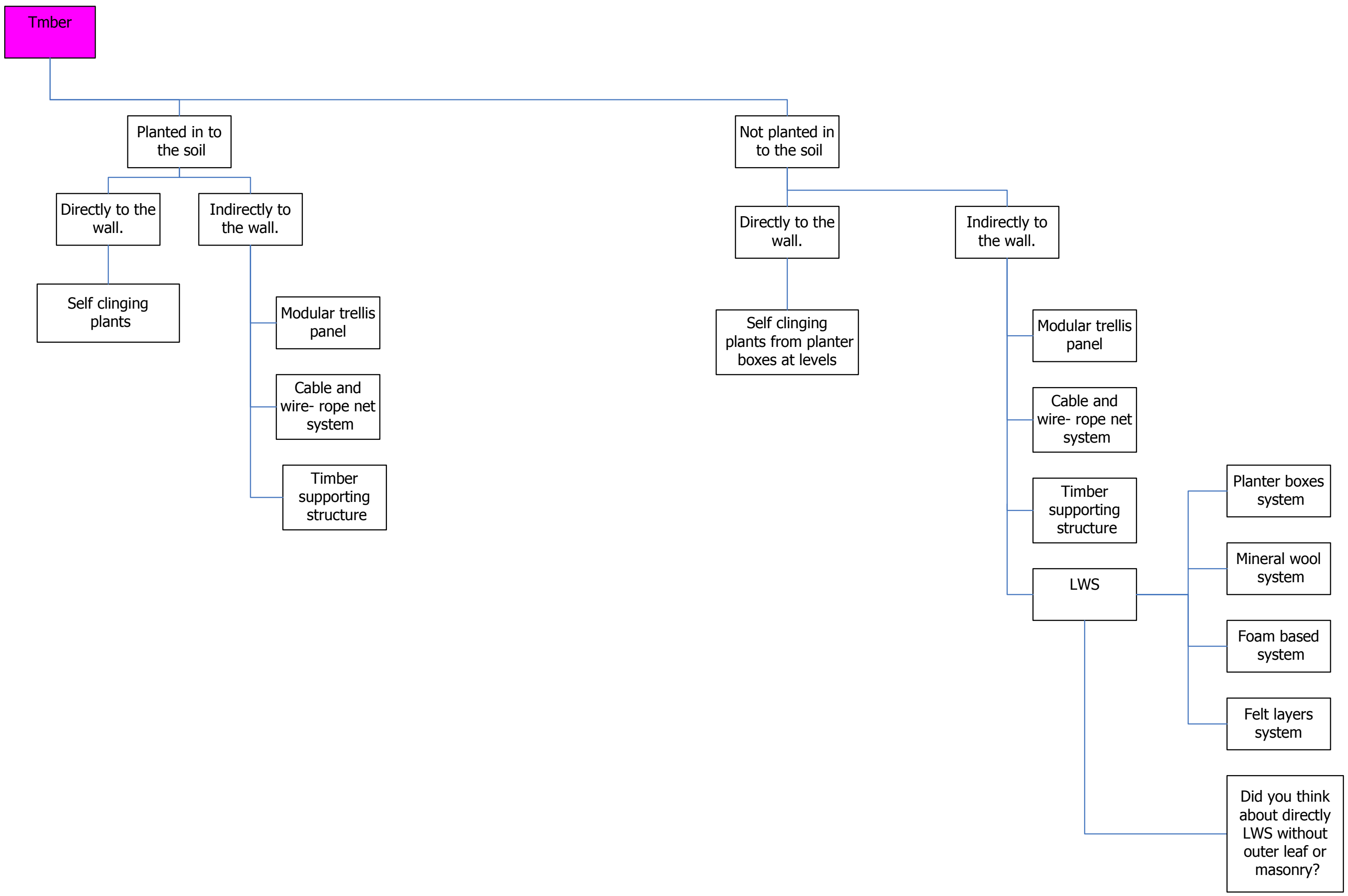

2C Present structure
Concrete
Is the structure a monument?
Yes
Contact appropriate authorities.
No
Is there cracking?
Yes
No
First perform restoration activities.
Our advice is a indirectly system associated with later cracking.
Not planted in to the soil
Indirectly to the wall.
Modular trellis panel
Cable and wire- rope net system
Timber supporting structure
LWS
Planter boxes system
Mineral wool system
Felt layers system
Foam based system
Planted in to the soil
Indirectly to the wall.
Modular trellis panel
Cable and wire- rope net system
Timber supporting structure
LWS
Planter boxes system
Mineral wool system
Felt layers system
Foam based system
Does it concern a sound barrier?
Yes
You can plant self climbing plants (self-clinging) from the ground, planted in the soil.
No
It is a building.
Planted in to the soil
Directly to the wall.
Self climbing plants (self clinging)
Indirectly to the wall.
Modular trellis panel
Cable and wire- rope net system
Timber supporting structure
LWS
Planter boxes system
Mineral wool system
Foam based system
Felt layers system
Not planted in to the soil
Directly to the wall.
Self climbing plants (self clinging)
Indirectly to the wall.
Modular trellis panel
Cable and wire- rope net system
Timber supporting structure
LWS
Planter boxes system
Mineral wool system
Foam based system
Felt layers system

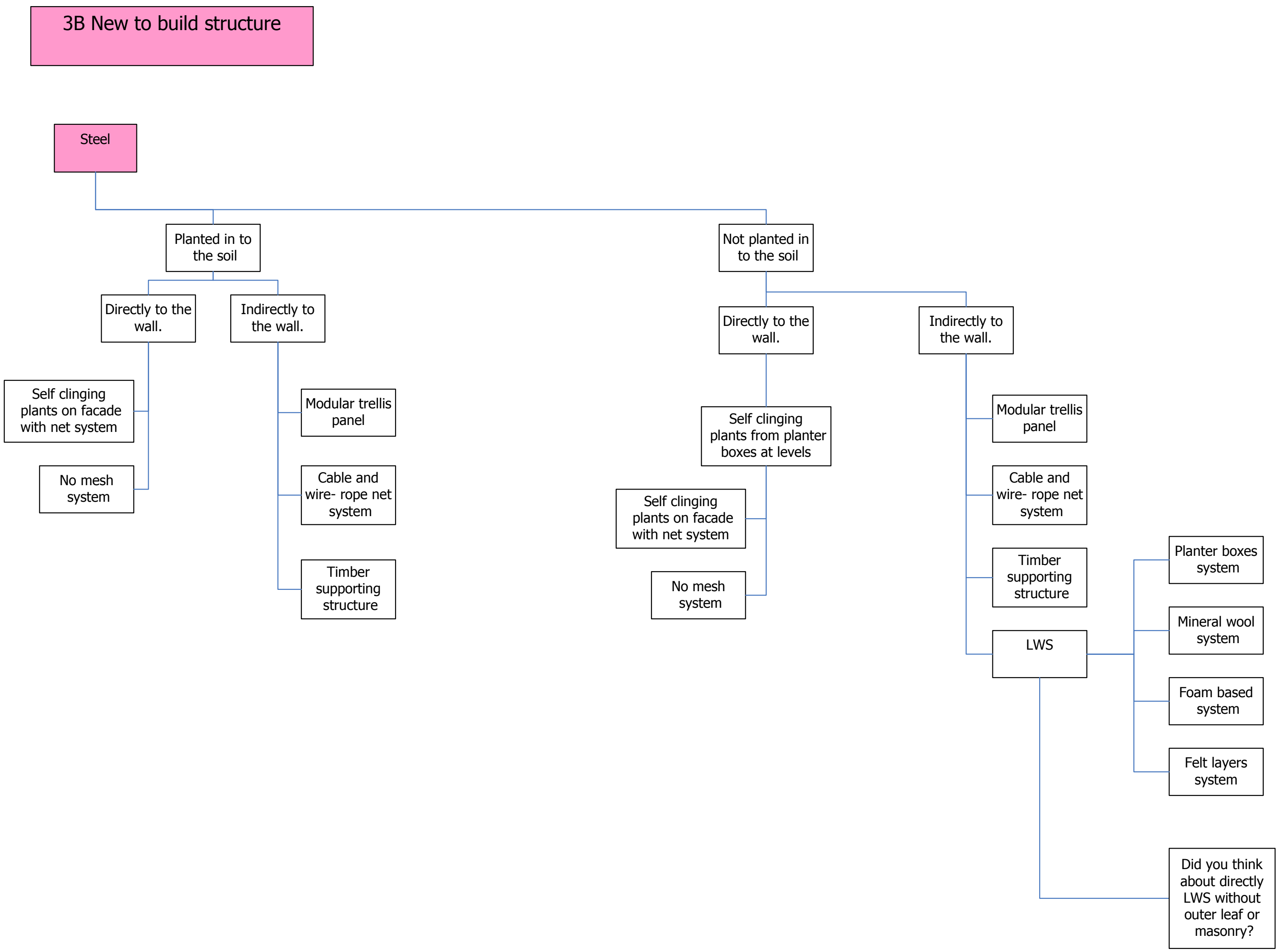

2D Present structure
Masonry
Is the structure a monument?
Yes
Contact appropriate authorities.
No
Does it concern a sound barrier?
Yes
Are the joints between the bricks in a good condition?
No
See 2D-1
No
Yes
First perform restoration activities. And than go farther with 'Yes' at the right side
Planted in to the soil
Not planted in to the soil
Directly to the wall.
Indirectly to the wall.
Directly to the wall.
Indirectly to the wall.
Self clinging plants (think about dilatation joints)
Modular trellis panel
Cable and wire- rope net system
Timber supporting structure
LWS
Planter boxes system
Mineral wool system
Foam based system
Felt layers system
Self clinging plants (think about dilatation joints)
Modular trellis panel
Cable and wire- rope net system
Timber supporting structure
LWS
Planter boxes system
Mineral wool system
Foam based system
Felt layers system

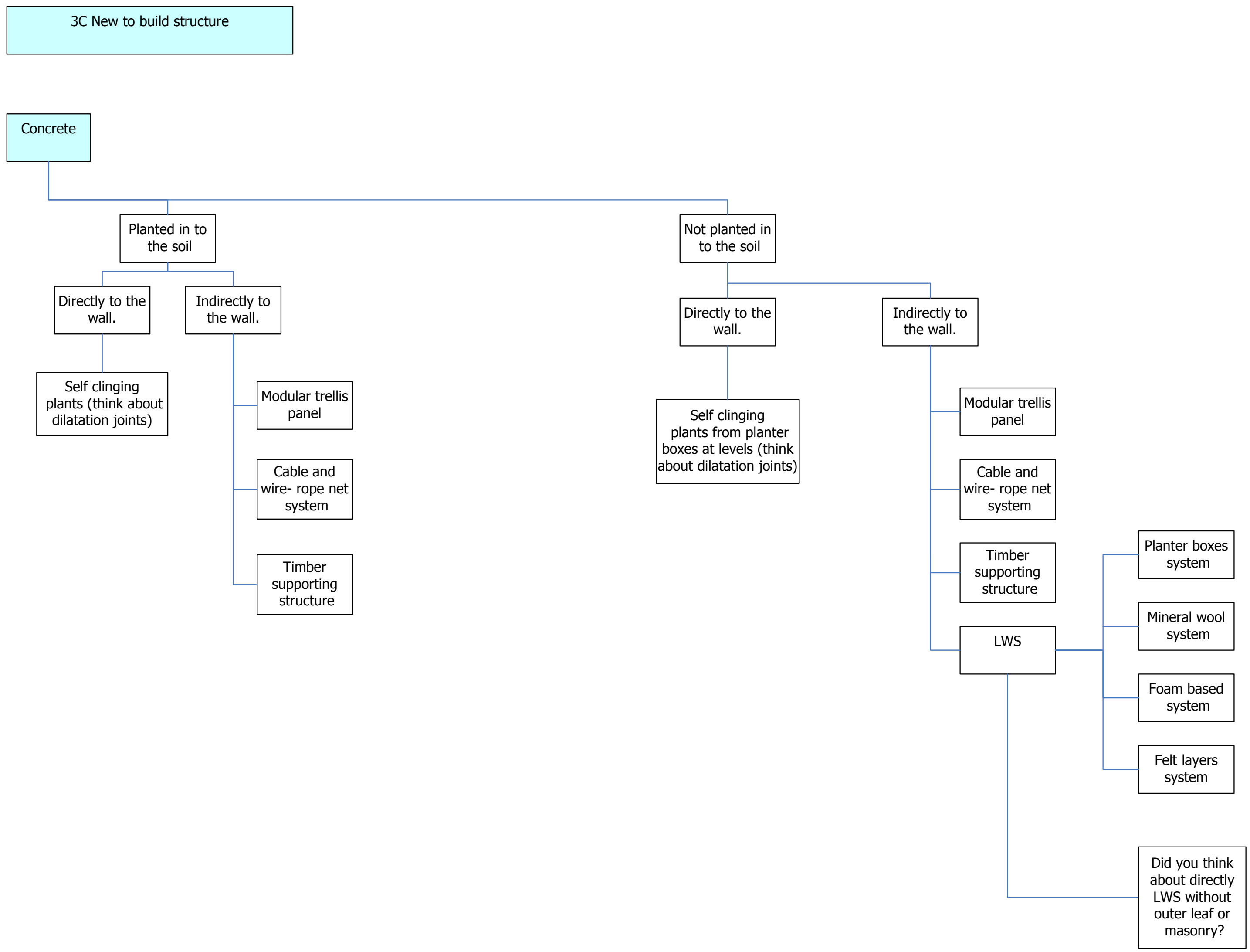

2D-1 Present structure
No
It is a building
Is it a bricks wall?
No
Is it a cavity wall without insulation?
Yes
No
Add insulation inside or outside.
Our advice is to use foamglass with self climbings plants.
Planted in to the soil
Directly to the wall.
Indirectly to the wall.
Self climbing plants (self clinging)
Modular trellis panel
Cable and wire- rope net system
Timber supporting structure
LWS
Planter boxes system
Felt layers system
Mineral wool system
Foam based system
Inside
Not planted in to the soil
Directly to the wall.
Indirectly to the wall.
Self clinging plants (think about dilatation joints)
Modular trellis panel
Cable and wire- rope net system
Timber supporting structure
LWS
Mineral wool system
Planter boxes system
Felt layers system
Foam based system
Yes
Do you want to apply insulation?
Yes
No
Outside
Our advice is to use foamglass with self climbing's plants.
Are there cricks?
Yes
No
First perform restoration activities. And than go farther with 'No' at the right side.
See 2D-1-1

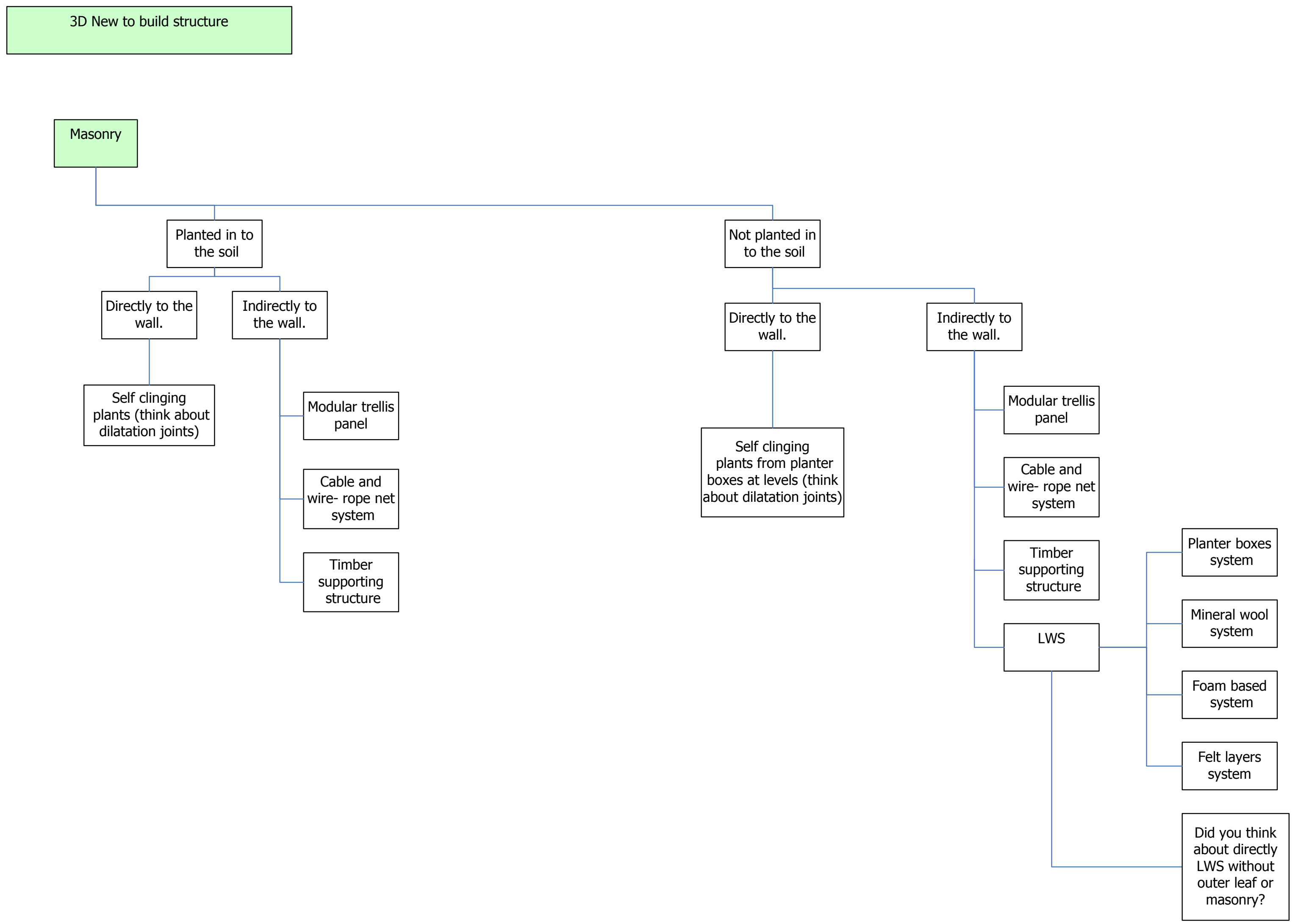

2D-1-1 Present structure
No
Is the quality of the bricks and joins between bricks sufficient?
No
First perform restoration activities. And than go farther with 'Yes' at the left side
Yes
Planted in to the soil
Not planted in to the soil
Directly to the wall.
Indirectly to the wall.
Self clinging plants (think about dilatation joints)
Modular trellis panel
Cable and wire- rope net system
Timber supporting structure
LWS
Foam based system
Felt layers system
Planter boxes system
Mineral wool system
Directly to the wall.
Indirectly to the wall.
Self clinging plants from planter boxes at levels (think about dilatation joints)
Modular trellis panel
Cable and wire- rope net system
Timber supporting structure
LWS
Foam based system
Felt layers system
Mineral wool system
Planter boxes system

3A New to build structure

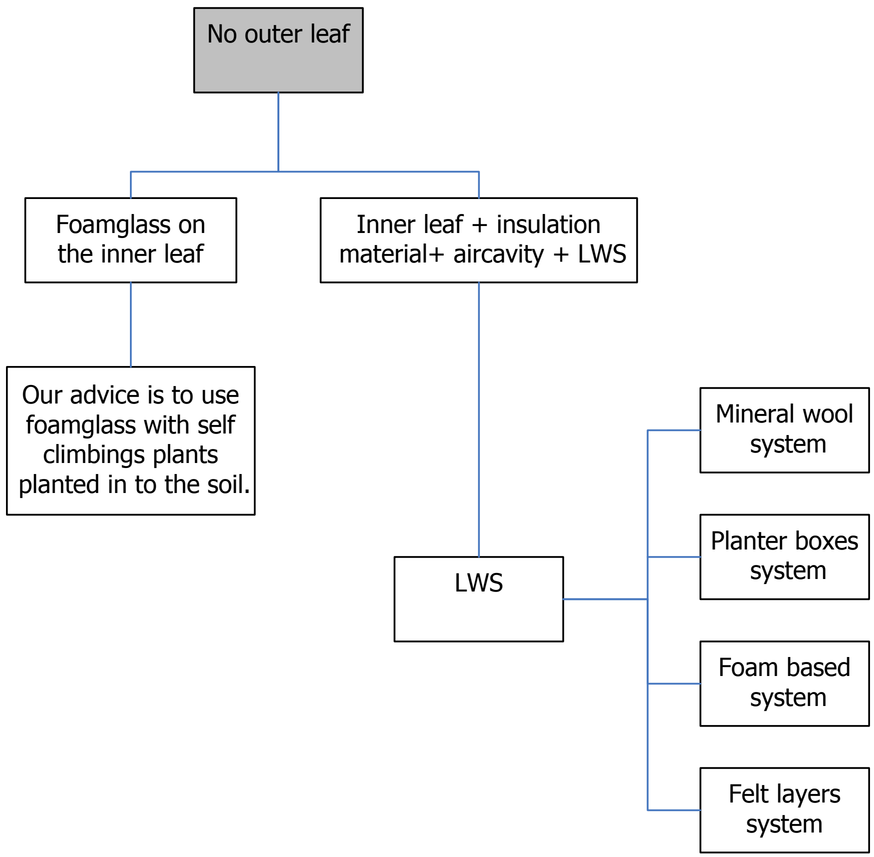



3B New to build structure
Steel
Planted in to the soil
Not planted in to the soil
Directly to the wall.
Indirectly to the wall.
Self clinging plants on facade with net system
No mesh system
Modular trellis panel
Cable and wire- rope net system
Timber supporting structure
Directly to the wall.
Indirectly to the wall.
Self clinging plants from planter boxes at levels
Self clinging plants on facade with net system
No mesh system
Modular trellis panel
Cable and wire- rope net system
Timber supporting structure
LWS
Planter boxes system
Mineral wool system
Foam based system
Felt layers system
Did you think about directly LWS without outer leaf or masonry?


3C New to build structure
Concrete
Planted in to the soil
Not planted in to the soil
Directly to the wall.
Indirectly to the wall.
Self clinging plants (think about dilatation joints)
Modular trellis panel
Cable and wire- rope net system
Timber supporting structure
Directly to the wall.
Indirectly to the wall.
Self clinging plants from planter boxes at levels (think about dilatation joints)
Modular trellis panel
Cable and wire- rope net system
Timber supporting structure
LWS
Planter boxes system
Mineral wool system
Foam based system
Felt layers system
Did you think about directly LWS without outer leaf or masonry?


3D New to build structure
Masonry
Planted in to the soil
Not planted in to the soil
Directly to the wall.
Indirectly to the wall.
Self clinging plants (think about dilatation joints)
Modular trellis panel
Cable and wire- rope net system
Timber supporting structure
Directly to the wall.
Indirectly to the wall.
Self clinging plants from planter boxes at levels (think about dilatation joints)
Modular trellis panel
Cable and wire- rope net system
Timber supporting structure
LWS
Planter boxes system
Mineral wool system
Foam based system
Felt layers system
Did you think about directly LWS without outer leaf or masonry?

3E New to build structure without outer leaf



8 Conclusions and recommendations

8.1 Introduction

In this part of the master thesis general conclusions and recommendations about vertical greening applications on building structures are included. Paragraph 8.2 reviews the results which are found during the master thesis project. Paragraph 8.3 gives a number of recommendations which can be studied in future, in order to improve the use of vertical greening on building structures and for practical applications.

The presented thesis deals with a general description of vertical greening systems and their configurations, condensation calculations and vapour diffusion through a wall structure combined with some vertical greening systems (*Hedera helix* directly to the wall, *Hedera helix* indirectly to the wall and LWS based on planter boxes). In addition a life cycle analysis (LCA) was applied to two living wall systems (LWS based on mineral wool and LWS based on foam substrate) which is an important part of this thesis.

8.2 Conclusions

This section highlights the outcomes which are found during the study. The objective and the main question of the experiment in this research project was, to know and recognise if there is any influence of vertical greening systems on a wall with respect to moisture transport and condensation compared with a bare wall. Besides this the sustainability aspects of vertical greening systems are investigated for some living wall systems (LWS based on mineral wool and LWS based on foam substrate) and this is also compared with a bare wall.

Vertical greening systems are divided in three main groups and ten subgroups as showed in figure 1.2. The main groups are:

- green façades; (traditional use of climbing plants against façade from the ground or from planter boxes with watering system)
- wall vegetation; (spontaneous growing of plants on structures like old walls and monuments)
- living wall systems (LWS); (pre-vegetated “prefabricated” modular panels or in situ applied panels), is a new application form of vertical green with a new technology.

Green façades refers to traditional use of climbing plants against façade from the ground or planter boxes. It is a process that typically requires a long-term (more than 30 years) growing period for covering whole façade. Wall vegetation refers to uncontrolled process whereby plants spontaneously grow on building materials. This group has also a long-term growing period. The main characteristics of the latter are that the plants are rooted in or on a building material (mostly stone or rock). Living wall systems (LWS) refers to pre-vegetated “prefabricated” modular panels or in situ applied panels with a relatively short (0-1 years) growing period. Living wall systems can be applied for indoor and outdoor applications.

The advantages and disadvantages of vertical greening systems determined via the literature study are as follows:

Advantages:
- filtering air particulates to improve air quality.
- reducing the urban heat island effect.

- providing sound insulation.
- moderating a building's internal temperature via external shading.
- creating a microclimate, which will help to alter the climate of a city as a whole.
- providing biodiversity and a natural animal habitat.
- protecting the wall against graffiti.
- improving the insulation properties in summer and winter.

Disadvantages:

- damage on façade in case of green façade directly to the wall.
- maintenance of vertical greening systems.
- costs of vertical green systems, especially living wall systems.
- irrigation systems.

An experimental setup was built in order to study in detail the effect of a green layer on the moisture gradient through a façade. The experimental setup is divided in two compartments with a test specimen (an insulated brick wall) and allows measurements with different boundary conditions (winter and summer temperatures). The measurements from the experimental setup (hotbox) show the effect of different vertical greening systems on the moisture transport through the greened insulated brick wall. From the results, it can be concluded that there is especially a positive effect of living wall systems on the thermal behaviour and moisture transport of buildings. Moisture transport can occur with applying green against the façade and the condensation inside the layers of the whole system stays between the limitations, according to Glaser method. The condensation takes place in winter and there is no condensation at summer measurements with a normal relative humidity of about 75%. LWS based on planter boxes shows condensation in different layers, while the direct and indirect greening systems condensate only in one layer of the structure (between insulation material and outer masonry layer). For preventive reasons it is advised to use vapour barrier to prevent the moisture transport better through the walls of the buildings with applying green (specially LWS) on it. As the literature it describes the absorbed moisture by the structure in the winter (60 days) should evaporate back in the summer (90 days), which is calculated in chapter 5 and shows that the measured vertical greening systems meet this requirement. For all condensation calculations a vapour diffusion resistance figure (μ) of 1.5 is assumed for vertical greening systems, which corresponds with the regulations that (μ≥1).

Applying of living wall systems (LWS) based on mineral wool and foam substrate considering the materials involved, have a negative influence on the environmental burden based on a life cycle analysis (LCA) as shown in paragraph 6.4. However not all of the benefits of vertical greening are totally quantified yet, either because of a lack of reliable data or incompatibility of the benefits with the different available tools (LCA). Those benefits are mainly related to the macro scale ecological and environmental benefits such as increased biodiversity, human health, the indirect effect of lowering urban city temperatures (decrease of energy demand, reduction of air pollution, etc.), increased humidity and improvement of the air quality through vegetation. When taking into account all the (until now unquantifiable) claimed advantages such as graffiti control, air quality improvement, sound insulation, social and economical aspects, ecological functions, etc. regarding greening the building with green façades or living wall systems, it can be a sustainable option.

The main conclusions are listed below.

1) Vertical greening systems are divided in three main groups: green façades, wall vegetation and living wall systems (LWS).
2) Vertical greening systems have no negative influence on condensation and vapour diffusion (moisture transport) through a wall, compared with a bare wall as found during the experiments.

3) There can be condensation during the winter period which does not exceed the limitations.
4) For all condensation calculations a vapour diffusion resistance figure (μ) of 1.5 is assumed for vertical greening systems.
5) Living wall systems have a more or less airtight texture and they are protecting the façade better against sunshine and (heavy) rains. This means that the temperature and moisture transport cannot take place easily.
6) The environmental burden profile for the living wall system based on mineral wool appears to be almost the same as living wall system based on foam substrate.
7) Both LWS based on mineral wool and LWS based on foam substrate have almost the same contribution to the energy savings for heating. But for the Mediterranean climate, a higher influence was noted for the cooling properties of the plants which are to recognise for all 6 vertical greening system tested in hotbox.
8) For the LWS based on felt layers, LWS based on mineral wool and LWS based on foam substrate in both climate types (Mediterranean and temperate) the environmental burden profile is higher than the benefits gained for heating and cooling in comparing to LWS based on planter boxes.
9) A decision tree helps to make choices with respect to materials, right type of vegetation, configuration, to avoid possible mistakes in the façade design and can end with optimal vertical green system(s) to use on the structure.

8.3 Recommendations

This part gives a number of recommendations for further research which can probably improve the use and application of vertical greening systems in future.

1) Larger dimensions for the hotbox specially the outside climate chamber could increase the accuracy of the results.
2) In practice, for preventive measures it is advisable to use vapour barriers in case of living wall systems.
3) Due to the advantages of vertical greening it should be applied more in the future, especially in dense urban areas.
4) The choice of different materials such as hard wood, HDPE, etc, instead of stainless steel and aluminium (commonly used) as supporting system for living wall systems, can lead to a more sustainable green building technology.
5) The decision tree should be worked out further in an automated computer programme so that it can be implemented in architectural software programs.

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Annex A

Supplies for the measurements

The following supplies are used for the measurements in the hotbox.

1. a computer with measurements software on it.
2. 28x thermocouple type T (copper constantan alloy)
3. 4x USB- 4718 (8 channel thermocouple USB Module)
4. 10x humidity sensors (Honywell)
5. Ni-daq hardware box
6. 9 x 'Philips IR light 100W E27 230V PAR38 Red glass'
7. 4x 'Paulmann Halogen 75W E27 240V PAR30 plant reflector lamp rose.
8. 2x hot-air gun 'STEINEL HL 1610S'
9. a high performance 'SIEMENS' freezer.
10. a refrigerator.
11. 2x exhaust type fan model "SIKU 100 PF".
12. 2x Pt-100 (temperature measurement supply)
13. Polyurethaan foam (PUR)

1. A computer with measurement software (Mp3) is used, which has the capacity to register the measurements data continuously (figure A.1). The thermocouples and humidity sensors from the inside of hotbox and from the specimen are connected to the computer. Thermocouples are connected to a USB-4718 channel and the humidity sensors are connected to a Ni-daq box which is connected to the computer via USB connections.

Figure A.1: computer with measurements software (Mp3) nearby the hotbox.

2. Thermocouple type T (copper constantan alloy) is used to measure the temperature transition across the specimen from left to right and also from right to left in both summer and winter condition (figure A.2). The thermocouples are connected to a USB- 4718 (8 channel Thermocouple USB Module) and thereafter to the computer.

Figure A.2: thermocouples (brown wires) used through the test specimen.

3. USB- 4718 (8 channel Thermocouple USB Module) has the function to convert the data from thermocouples to digital numbers and it transmits the data to the computer (figure A.3).

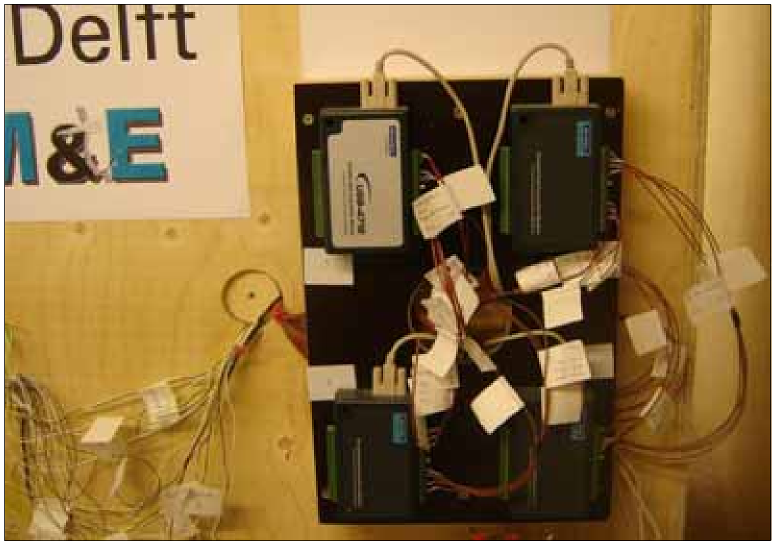

Figure A.3: USB- 4718 (8 channel thermocouple USB Module).

4. Humidity sensors (Honywell) are used to measure the humidity across the specimen and in the climate chambers (figure A.4). The humidity sensors send the data to the Ni-daq box and after that the data reaches the computer.

Figure A.4: humidity sensors inside the air cavity, photo made during the construction.

5. Ni-daq hardware box is used to translate the data from the humidity sensors to the digital system (figure A.5). After that the Ni-daq hardware box sends the data to the computer.

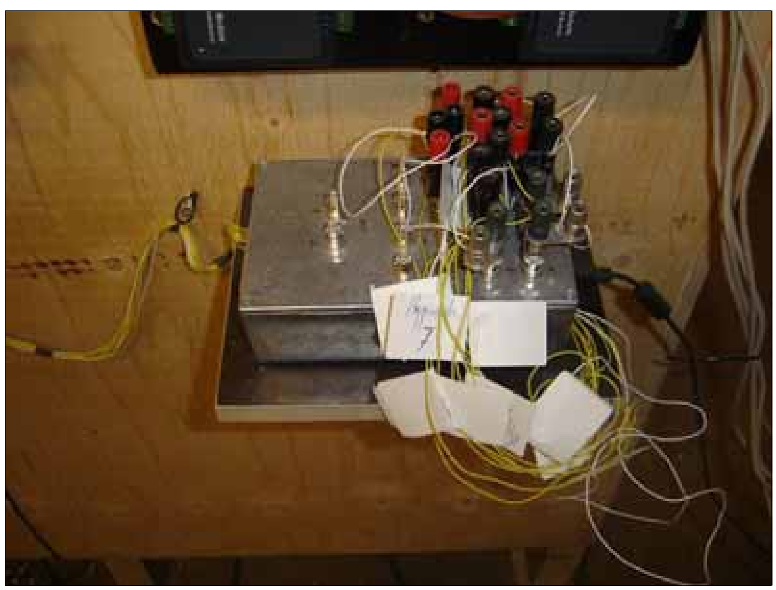

Figure A.5: Ni-daq hardware box.

6. 'Philips IR light 100W E27 230V PAR38 Red glass' lights are used to simulate and realize sun shine in the hotbox (figure A.6). The IR lights are installed on a wooden vertical panel, which is placed with a distance of almost 1 m from the test specimen.

7. 'Paulmann Halogen 75W E27 240V PAR30' plant reflector lamp rose, are used to create the necessary amount of light which is needed for growing of the plants (figure A.6).

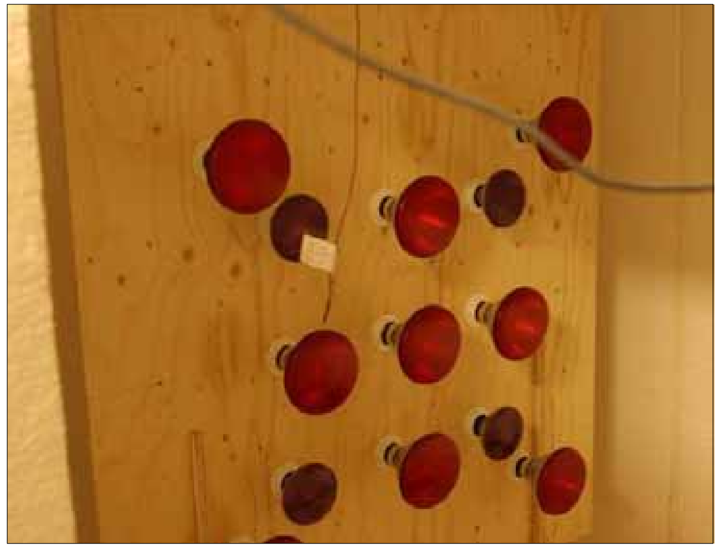

Figure A.6: IR lights (red and big size), plant reflector lamps (rose and small size) on the same panel.

8. Hot-air gun 'STEINEL HL 1610S' is used to realize convection heat in the hotbox (figure A.7). A second hot-air gun is used to make also the outside air-cavity (insulation cover) warm, during the summer measurements.

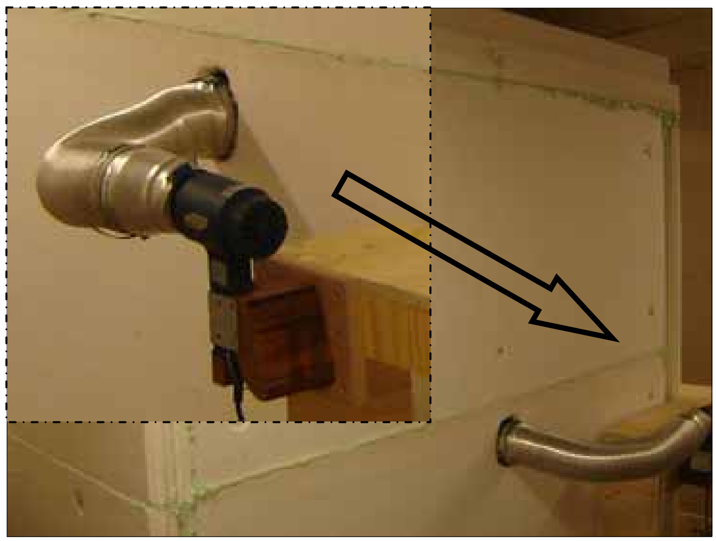

Figure A.7: Hot-air gun connection with an aluminium pipe, outside the hotbox.

9. A high performance 'SIEMENS' freezer (cooling unit) is used to create the winter (freezing) situation inside the hotbox (figure A.8).

10. A refrigerator (cooling unit) is used to make the outside air cavity (insulation cover around the hotbox) cold for the winter condition measurements (figure A.8). The usage of the refrigeration helps to minimize the loss of cold air from inside the hotbox.

Figure A.8: A refrigerator (cooling unit) used for outside air cavity (insulation cover around the hotbox) and a high performance 'SIEMENS' freezer for inside the hotbox.

11. Exhausts Ventilators are used by the two cooling units inside the aluminium pipes to pump the cold air from the cool units to the hotbox and to the outside air cavity (insulation cover around the hotbox).

12. Pt-100's (temperature measurement supply) are used to regulate the amount of heat in the hotbox (figure A.9). It turns automatically on and off to control the decrease and increase of the temperature inside the hotbox and also inside the air cavity around the hotbox.

Figure A.9: Pt-100, temperature measurement supply.

13. Polyurethane foam (PUR) is used for sealing the hotbox door before each measurement session. PUR-foam is also used to make the air cavity around the hotbox as tight as possible against leakages.

Annex B

The relative humidity graphs

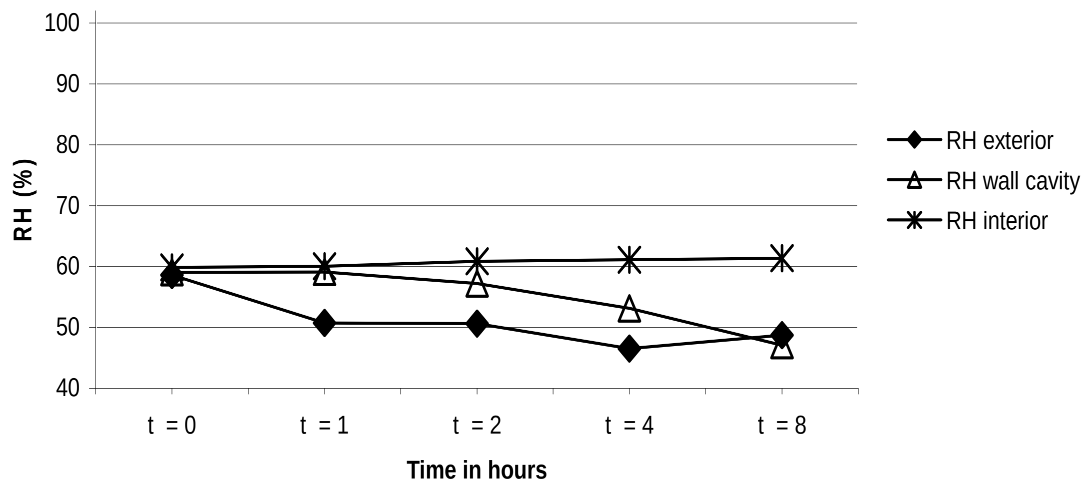

Figure B.1: relative humidity movement during the summer measurement, for a bare wall.

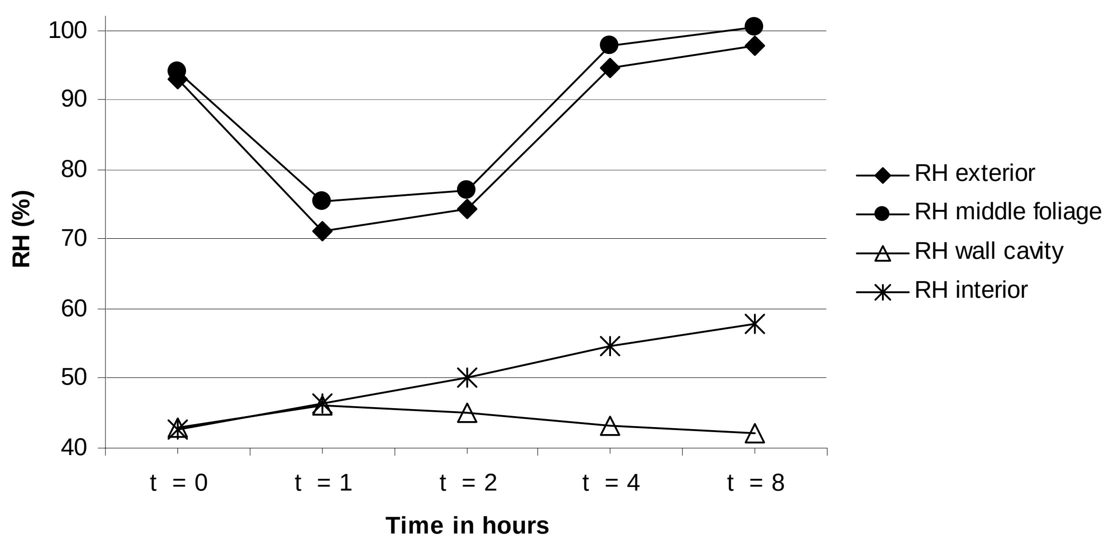

Figure B.2: relative humidity movement during the summer measurement, for a direct vertical greening system compared with a bare wall.

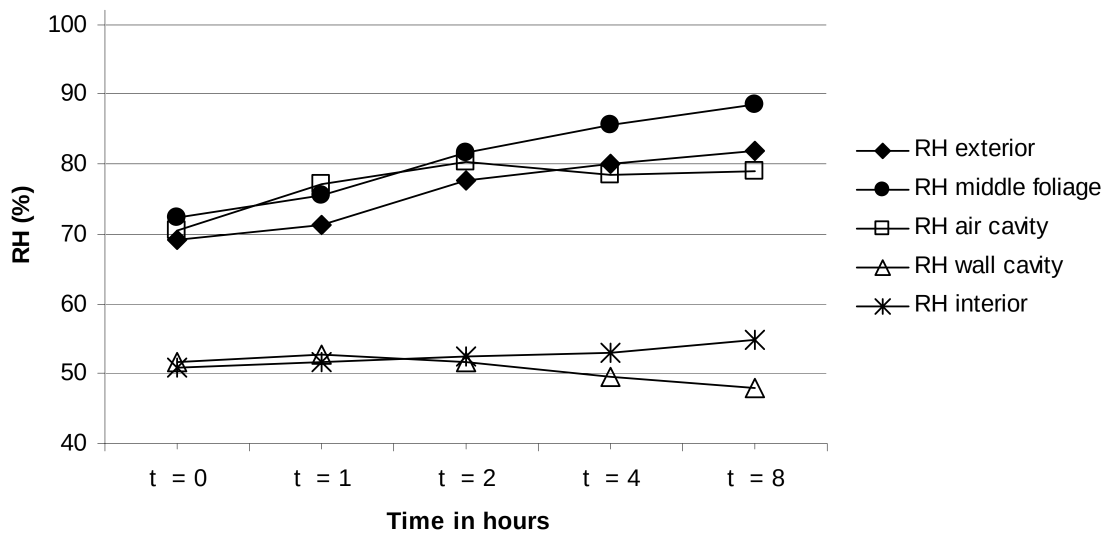

Figure B.3: relative humidity movement during the summer measurement, for an indirect vertical greening system compared with a bare wall.

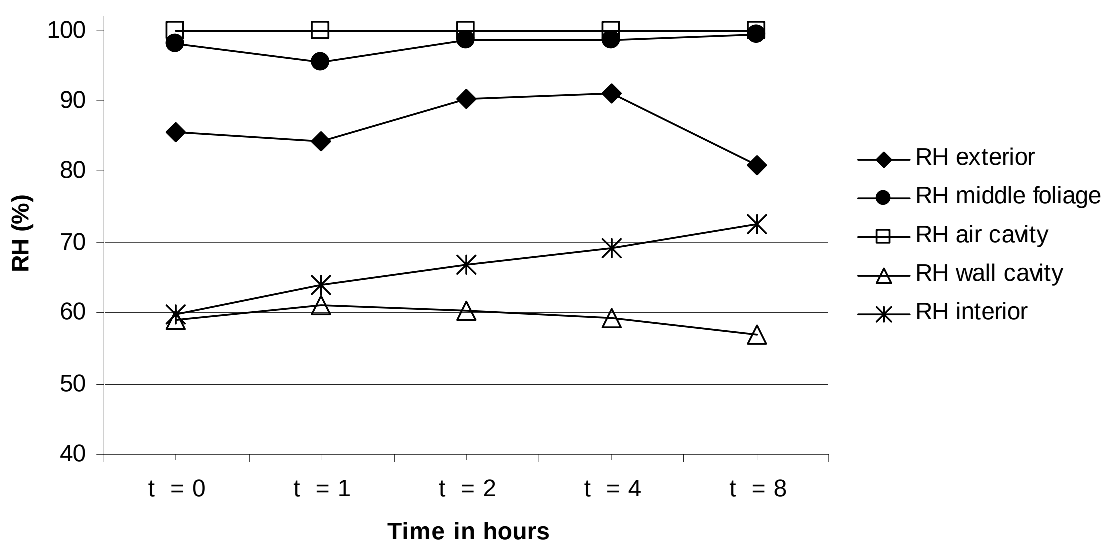

Figure B.4: relative humidity movement during the summer measurement, for a living wall system based on planter boxes compared with a bare wall.

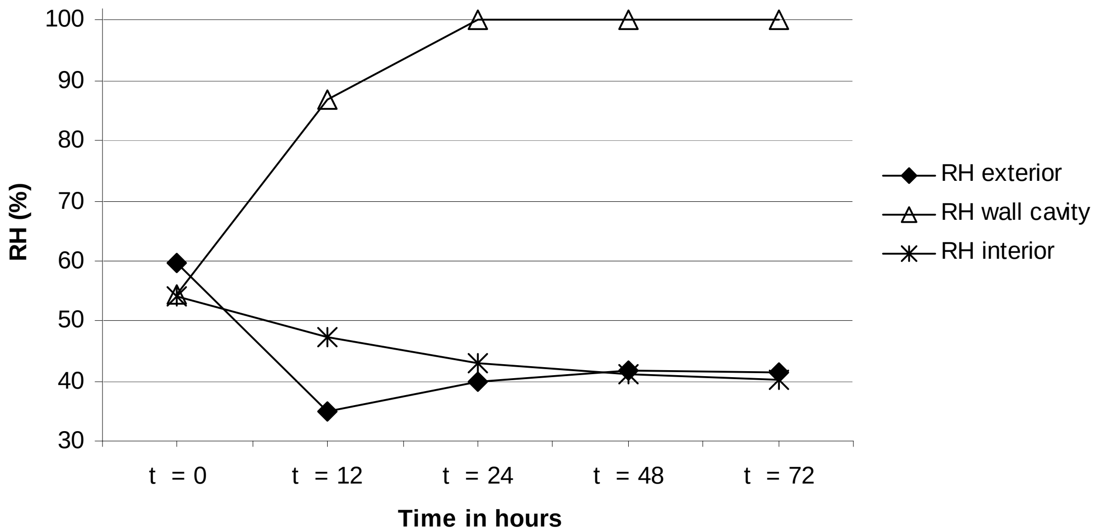

Figure B.5: relative humidity movement during the winter measurement, for a bare wall.

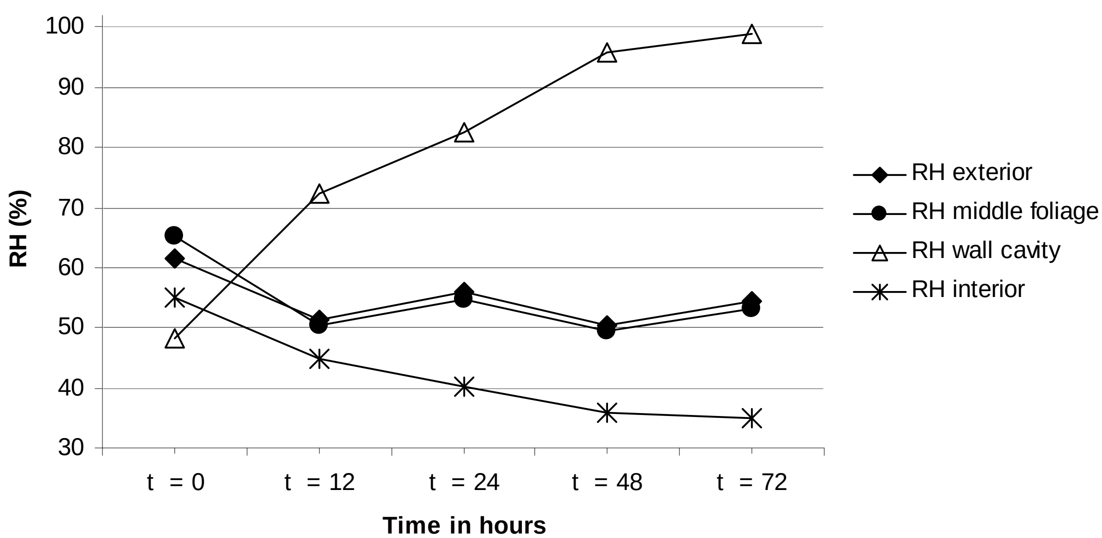

Figure B.6: relative humidity movement during the winter measurement, for a direct vertical greening system compared with a bare wall.

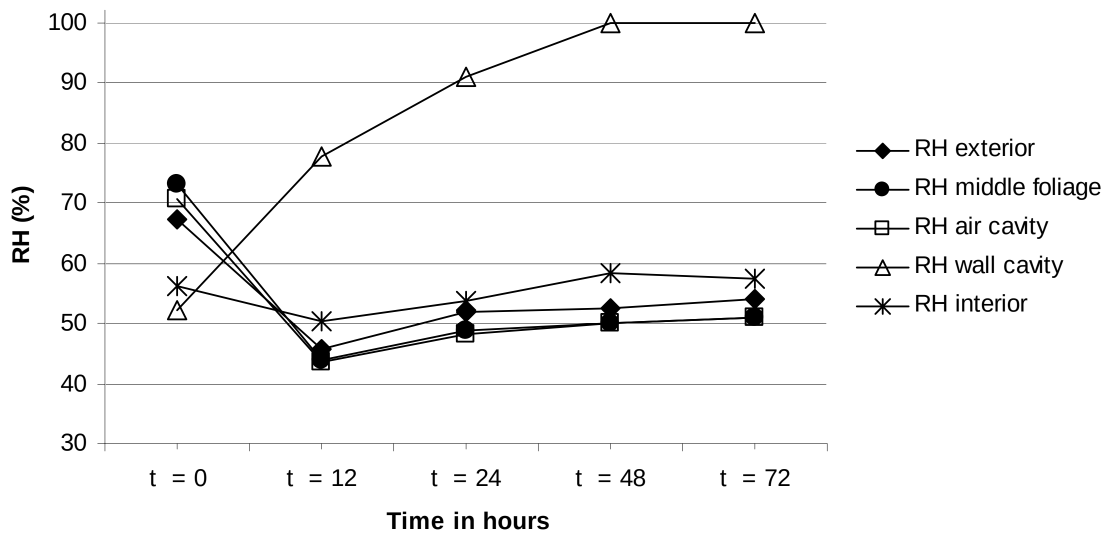

Figure B.7: relative humidity movement during the winter measurement, for an indirect vertical greening system compared with a bare wall.

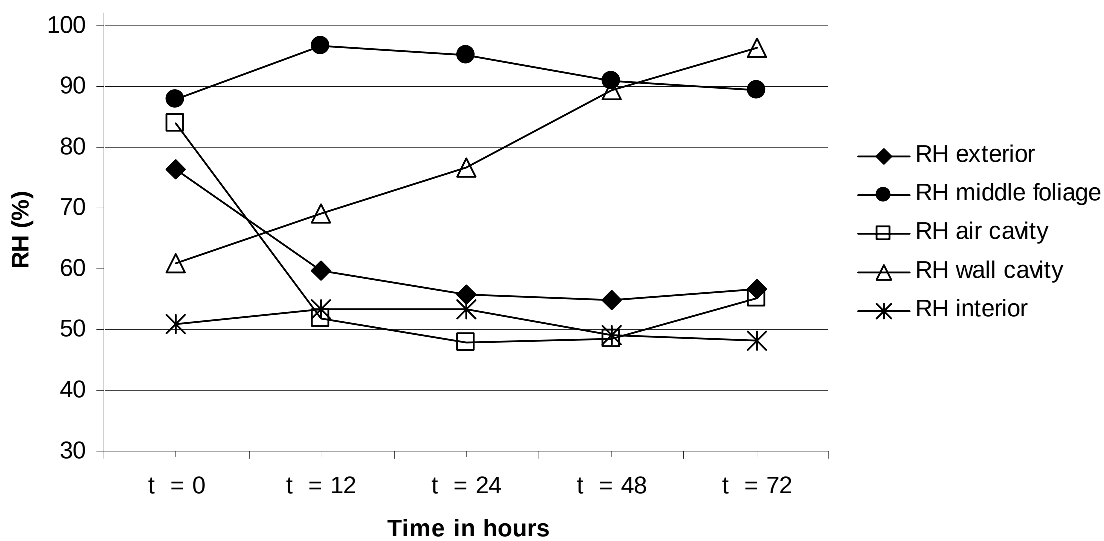

Figure B.8: relative humidity movement during the winter measurement, for a living wall system based on planter boxes compared with a bare wall.

Annex C

Maximum vapour pressure as function of the temperature (Tammes en Vos, 1984).

c_{max}		De verzadigde waterdampspanning p_s in N/m²									
g/m³	Temp. °C	,0	,1	,2	,3	,4	,5	,6	,7	,8	,9
39,56	+ 35	5627	5657	5688	5720	5752	5784	5816	5848	5880	5912
37,54	34	5323	5352	5381	5412	5443	5472	5503	5533	5564	5595
35,62	33	5033	5061	5090	5118	5146	5176	5205	5234	5264	5293
33,77	32	4757	4785	4812	4838	4866	4893	4921	4949	4977	5005
32,02	31	4496	4521	4546	4573	4598	4625	4650	4677	4704	4730
30,34	30	4245	4270	4294	4319	4344	4369	4393	4418	4443	4469
28,73	29	4007	4031	4054	4078	4102	4125	4149	4173	4197	4221
27,21	28	3782	3803	3826	3848	3871	3893	3915	3939	3962	3984
25,75	27	3567	3588	3610	3630	3651	3674	3695	3716	3738	3760
24,36	26	3363	3383	3403	3423	3443	3463	3484	3504	3530	3546
23,05	25	3169	3188	3207	3226	3246	3264	3284	3303	3323	3343
21,78	24	2985	3003	3022	3040	3058	3076	3095	3114	3132	3151
20,55	23	2811	2828	2844	2861	2879	2896	2915	2932	2949	2967
19,43	22	2645	2661	2677	2693	2710	2727	2744	2760	2778	2793
18,35	21	2488	2504	2518	2535	2549	2565	2581	2597	2613	2629
17,28	20	2340	2353	2368	2382	2397	2412	2428	2442	2457	2473
16,30	19	2198	2212	2225	2240	2253	2268	2281	2296	2310	2325
15,37	18	2065	2077	2090	2104	2117	2130	2144	2157	2170	2184
14,47	17	1938	1950	1962	1978	1988	2001	2014	2026	2034	2052
13,65	16	1818	1830	1842	1854	1866	1878	1890	1902	1914	1926
12,85	15	1706	1717	1728	1739	1750	1761	1773	1784	1796	1808
12,07	14	1599	1609	1619	1630	1641	1651	1662	1673	1684	1696
11,35	13	1498	1507	1518	1527	1538	1547	1558	1569	1578	1589
10,65	12	1403	1413	1422	1431	1441	1450	1459	1469	1478	1489
10,01	11	1313	1321	1331	1339	1349	1358	1366	1375	1385	1394
9,40	10	1229	1237	1245	1253	1262	1270	1278	1287	1295	1305
8,82	9	1148	1156	1164	1172	1179	1187	1195	1203	1212	1220
8,27	8	1072	1080	1087	1095	1103	1110	1118	1126	1132	1140
7,76	7	1002	1008	1016	1023	1030	1036	1044	1051	1059	1066
7,28	6	935	942	948	955	962	968	975	982	988	995
6,83	5	872	879	884	891	898	903	910	916	923	928
6,40	4	814	819	826	831	836	843	848	855	860	867
5,99	3	758	763	768	775	780	786	791	796	802	808
5,59	2	706	711	716	722	727	732	736	742	747	752
5,21	1	657	661	667	671	676	681	685	691	696	701
4,84	+ 0	611	615	620	624	628	633	637	643	647	652
4,84	– 0	611	605	600	596	591	587	581	576	572	567
4,48	– 1	563	557	553	548	544	539	535	531	525	521
4,14	– 2	517	513	508	504	500	496	492	488	484	480
3,82	– 3	476	472	468	464	460	456	452	448	444	440
3,53	– 4	437	433	429	425	423	419	415	412	408	404
3,26	– 5	401	397	395	391	388	384	381	377	375	371
3,01	– 6	368	365	361	359	356	352	349	347	344	340
2,77	– 7	337	335	332	329	327	323	320	317	315	312
2,55	– 8	309	307	304	301	299	296	293	291	288	285
2,34	– 9	283	281	279	276	273	271	269	267	264	261
2,15	– 10	260	257	255	252	251	248	245	244	241	240
1,98	– 11	237	235	233	231	229	227	225	223	221	219
1,82	– 12	217	215	213	211	209	207	205	204	201	200
1,67	– 13	199	196	195	193	191	189	188	185	184	183
1,53	– 14	181	179	177	176	175	173	171	169	168	167
1,41	– 15	165	164	163	160	159	157	156	155	153	152
1,29	– 16	151	149	148	147	145	144	143	141	140	139
1,18	– 17	137	136	135	133	132	131	129	128	127	125
1,08	– 18	124	124	123	121	120	119	117	116	116	115
0,99	– 19	113	112	111	111	109	108	107	105	105	104
0,90	– 20	103	101	101	100	98,7	98,7	97,4	96,0	94,7	94,7