The Green Building Envelope

Vertical Greening

Proefschrift

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door

Marc OTTELÉ

civiel ingenieur
geboren te Rotterdam

Dit proefschrift is goedgekeurd door de promotor:

Prof. dr. ir. E.M. Haas

Copromotor: Dr. ing. H.D. van Bohemen

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"If the bee disappeared off the surface of the globe then man would only have four years of life left. No more bees, no more pollination, no more plants, no more animals, no more man."

Albert Einstein

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List of symbols

Symbol	*Quantity*	*Unity*
A	*area (perpendicular to the density of heat flow)*	m^2
d	*thickness*	m
λ	*thermal conductivity*	$W/(m\cdot K)$
R_i	*internal surface resistance*	$(m^2\cdot K)/W$
R_e	*external surface resistance*	$(m^2\cdot K)/W$
R_T	*thermal resistance construction*	$(m^2\cdot K)/W$
R_{plant}	*thermal resistance of plant layer*	$(m^2\cdot K)/W$
R_{LWS}	*thermal resistance of living wall system*	$(m^2\cdot K)/W$
ε	*emesitivity*	---
	Stefan-Bolltzmann coefficient 57.610^{-9}	$W/(m^2K^4)$
U	*thermal transmittance*	$W/(m^2\cdot K)$
q	*heat flow density*	W/m^2
α_i	*interior heat transfer coefficient*	$W/m^2\cdot K$
α_e	*exterior heat transfer coefficient*	$W/m^2\cdot K$
$\alpha_{convection}$	*convective heat transfer coefficient*	$W/m^2\cdot K$
$\alpha_{radiation}$	*radiative heat transfer coefficient*	$W/m^2\cdot K$
T_i	*interior air temperature*	K
T_e	*exterior air temperature*	K
T_n	*temperature at layer n*	K
T_e	*exterior air temperature*	K
ΔT	*temperature difference between two layers*	K
RH	relative humidity	%
V	water vapour content of the air	kg/m^3
v_s	maximum water vapour content of the air	kg/m^3
P_v	partial pressure of air	Pa
TSP	total suspended particles in the air	µm
PM_X	particulate matter	µm
PM_{10}	coarse particles	µm
$PM_{2.5}$	fine particles	µm
$PM_{0.1}$	ultra fine particles	µm

1 Green building envelopes in city ecology

1.1 General introduction

Since the beginning of the twentieth century research into the use of green inside the cities increased substantially. In particular the amount of publications, articles and research focused on the use of green roofs and green façades has been increased in recent years (Köhler, 2008). Despite the interest (under city dwellers, architects, city planners, policy makers and scientists) in the use of a green building envelope corresponding to the positive claims of green done in the past, hard data about the effect of urban green is sometimes missing or not well studied yet. Nowadays the environmental impact of buildings on the inner and outer climate becomes more and more apparent. Green buildings are designed to reduce the overall impact of the built environment on human health and the natural environment. The buildings in which we spend a great pad of our life protect us from nature's extremes, yet they also affect our health and environment in countless ways (EPA, 2010). The U.S. environmental protection agency (EPA) has classified the impacts of the built environment (table 1.1). Green building strategies not only stand for sustainable materials in their construction (e.g., reused, recycled-content, or made from renewable resources, but also making use of natural processes (e.g., shading effect of trees, insulation capacities of green roofs and green façades, mitigation of urban heat due to evapotranspiration). The green building strategy in the presented research concentrates on one key aspect of the "greening process" namely the use of plants on and around urban buildings.

Table 1.1 Impacts of the built environment (EPA, 2010).

Aspects of built environment	Consumption	Environmental effects
siting	energy	waste
design	water	air pollution
construction	materials	light pollution
in use	natural resources	water pollution
maintenance		indoor pollution
renovation		heat islands
deconstruction		storm water runoff
		noise

Why are city dwellers more and more interested in focussing on the innovative use of a green building envelope (greening of buildings with vegetation)? If you wonder this, a walk around in a city looking at façades with and without plants, looking for the enhancing effect that even a thin cover of mosses or algae can have on the visual impact of the façade will provide probably a positive answer. A stark, unbroken line of façades in cities is often perceived as sleepy. When few green is added the prospect is much more pleasing; sight moves from one group of plants to the next group of plants and the straight line of the paved façades is broken (Johnston et al., 2004).

The use of plants rooted in the soil at the base of façades by many architects and landscape architects is indicative of the value placed upon there presence in the urban landscape (Laurie, 1977). Structures covered with green are a symbol of building in harmony with architecture and nature. The garden-city movement at the end of the 19^{th} century may be seen as one of the first ecological reactions to industrialisation in urban areas (Kaltenbach, 2008).
Beside the positive value of green on the visualisation by humans in cities there is much more that can be linked to the influence of urban green on the climate of a city. Good examples are increasing the ecological value (biodiversity), mitigating of urban heat island, insulating properties and air quality improvement. To deal with these problems in dense urban areas often one-sided solutions are chosen. With the increased focus on ecological impacts of human activities on our environment the attention is shifted more and more to integrated solutions. Ecological engineering, can contribute to integrated solutions. Ecological engineering is an applied and multidisciplinary science; it is integrating human activities with the natural environment, so that both have advantage in designing and refurbishing of constructions. Conservation and the development of biodiversity are central in the designing process. Dense and paved cities need an appropriate development which incorporates an ecological approach to building and landscape design with respect to linking functions such as water management, air pollution reduction, energy conservation, the recycling of waste (water) and nature conservation (biodiversity).

One promising option for dense urban cities is the greening of buildings (Johnston et al., 2004). By strategically adding 'green skins' in this way, it is possible to create a new network of vegetation linking roofs, walls, courtyards, streets and open spaces. This is particularly important in the city centres where vegetation may cover only about one third of the land surface, compared with 75%-95% in the outer suburbs (Johnston et al., 2004).
Green façades as well as extensive and intensive green roofs increase the percentage of greenery in urban areas and will bring back the vanishing green space. The beneficial effect of green roofs and green façades lies mainly in the use of built surfaces. In urban environments there is a lack of green spaces (Bezemer et al., 2003) although the spatial strategy policy (spatial strategy, 2006) an amount of green has designated within the urban area of 75 m^2 per dwelling. It appears that this amount of green is not achieved in the larger and more densely populated cities in the Netherlands (Bezemer et al., 2003).

Greening the exterior of buildings (façades, roofs) provides numerous ecological and economic benefits, including storm water management, energy conservation, and mitigation of the urban heat island effect, reducing air pollutants, increased longevity of building materials, as well as providing a more aesthetically pleasing environment in which to work and live (Johnston et al., 2004; Getter et al., 2006; Minke, 1982; Krusche et al., 1982). Literature review done by Peck et al (1999) shows for example the benefit of green roofs on the inner temperature in buildings. Under a green roof without cooling indoor temperatures were found at least 3-4 °C lower than the outdoor temperature between 25 and 30 °C. This actually stipulates the functioning of greenery at the building level and gives also insight in the opportunities of greening our dense urban areas.

When people are asked for the motive of having green or nature in their neighbourhood or in their region, the answers can be simplified to motives of quality of life, health, economy and nature, regardless of the type of green public space that one has in mind. A more pleasant (living/working) environment creates the conditions for pleasant meetings and for relaxation in between (RLG, 2005).
Also the recovery from stress and tiredness is positively influenced by natural greenery, research shows that only the view to greenery is already sufficient (Health council, 2004; Ulrich, 1983). Due to a higher humidity level created by the evapotranspiration of water by plants a more pleasant microclimate is created, due to this the productivity of employees is stimulated (TNO, 2006). The architectural design of housing and, correspondingly, the identity of a neighbourhood and the city are positively influenced by a green area. Thereby it is the perception of natural elements that plays a major role for people. The value of real estate is increasing when it is present nearby green. Twelve percent of the value of a house is due to green at the backside of the house. Seven percent of the value is determined by the presence of a park in front or behind the house (RLG, 2005).
Green can be used for the retention of water as a consequence the sewer system can be tailored to lower the peak concentrations and to improve the water quality in the period of heavy rain. This subsequently can lead to savings on investments in sewer and water purification installations (Heidt and Neef, 2008, RLG, 2005). Green offers a variety of plants and animals; as a result of this many species can establish or maintain themselves in an urban environment. The biodiversity in cities is generally higher than in agricultural areas but lower than in the rural area (Natural Balance, 1999). The urban area offers a unique lodging to some specific types by the substrate (mostly brick, limestone and masonry (Darlington, 1981)) and the urban microclimate, such as wall vegetation and mosses. One of the characteristics that set a city apart from its rural surroundings is the altered climate that prevails over urban environments. Comparing rural areas with the urban areas differences can be found in solar input, rainfall patters and temperature. According to Heidt and Neef (2008) and Gilbert (1991) solar radiation, wind speed, air temperature, relative humidity and precipitation can vary significantly in the built environment (see also table 1.2).

Modern cities need to provide a visual stimulus but are often paved with brick, stone, asphalt and concrete. Plants and especially green façades can break paved surfaces when they are incorporated in the urban landscape. From the point of view of providing inhabitants with the impression of living in the rural area, vertical architecture presents an undeniable advantage since theoretically the system can be multiplied almost without limit throughout a city (Lambertini, 2007). Whereas space is limited, green façades and green roofs add a new and wider visual interest to the city scene.

Table 1.2 Climatic parameters of built-up areas compared with surrounding rural areas according to Gilbert (1991).

Climatic parameters	Characteristics	Compared to the surrounding area

Air pollution	Gaseous pollution	5 - 25 times more
Solar radiation	Global solar radiation	15 - 20% less
	Ultraviolet radiation	15 - 20% less
	Duration of bright sunshine	5 - 15% less
Air temperature	Annual mean average	0.5 - 1.5 °C higher
	On clear days	2 - 6 °C higher
Wind speed	Annual mean average	15 - 20% less
	Calm days	5 - 20% more
Relative humidity	Winter	2% less
	Summer	8 - 10% less
Clouds	Overcast	5 - 10% more
Precipitation	Total rainfall	5 - 10% more

Summarizing beside the visual aspect the presence of urban green has an effect on the ecological, economical and social function (Heidt and Neef, 2008) (figure 1.1). The ecological function of urban green may particularly be associated with increasing biodiversity, air quality, water quality and climate mitigation. The economical function of greenery is more difficult to quantify because mainly (indirect) long-term securities are involved. The indirect effects of urban green are among other things, increased estate values, energy savings for cooling and heating but also for example earnings from increased tourism.
Social functions of urban greenery lay mainly in the social cohesion, it brings people together. Parks, recreation areas, green roofs and façades provide meeting places for local residents, minorities, young and old people. Due to this social cohesion as side effect can be described namely increased mobility.

The skin of cities can be transformed into living landscapes were dwellers and nature can take advantage of numerous benefits that come from growing vegetation on and around buildings. Due to these benefits it is not only a fashionable gesture nor a cosmetic exercise, the greening of urban buildings is simply a highly rational thing to do (Johnston et al., 2004).

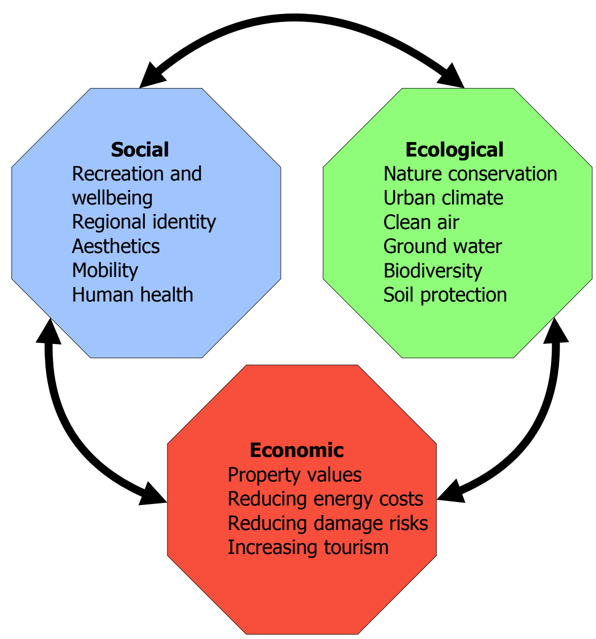


Figure 1.1 Economic, social, and ecological functions and objectives of urban green space management and sustainable urban land use with their interactions according to Heidt and Neef (2008).

1.2 Research objectives

The principal aim of the research, carried out during this doctoral thesis is to obtain insight in the (potential) contribution of façades to improve the air quality, the benefits of vertical green on building physics, especially in relation to insulation properties. Also the ecological aspect of vertical greened façades will be incorporated in the research. The objectives of this research can be formulated as:

- Obtain insight in the relation between vegetation and fine dust particles and how to quantify these particles on leave surfaces.
- Determine In a quantitative manner the contribution of vertical green on the building physical properties (heat transfer, moisture transport) of a construction.
- To study the sustainability aspect of vertical greening systems.

With the given objectives the approach of the investigation is still not determined; the approach will be briefly discussed in this section.
A literature study will analyze the main sources of air pollution in relation with vegetation, additional the thermal behaviour of greened surfaces will be examined. The research will have an explorative character and there where experimental research is necessary to obtain data, experiments will be conducted.

1.3 Research questions

The main research questions are:

- What are the possibilities for vegetation to form a part of the façade and how can we classify vertical greening systems?
- Accumulate vegetation more fine dust particles than other surfaces?
- What happens with accumulated particles once adhered on the leave surface?
- What is the contribution of vertical greening systems to the heat resistance of a façade?
- What is the effect of green façades and living walls on the temperature gradient through a construction in summer and winter?
- Is the air flow influenced inside the foliage or between a façade and vertical greening system?
- How durable and sustainable is a green façade or living wall system (with regard to the life span, costs, benefits, environmental burden, etc.)?
- Why green façades and living wall concepts among existing traditional cladding techniques?

1.4 The thesis methodology and chapter scheme

The thesis comprises seven chapters. The considerations fall into three basic sections: the literature overview, theoretical and experimental research and conclusions and achievements.

The second and third chapter is reserved for the literature study and to identify different vertical greening principles, whereby chapter three goes more in depth related to the outline of this thesis; the effects of vertical green.

In chapter four compromises to the relation between fine dust particles and the possibility of vertical green to counteract with this increasing problem. An electron microscope (ESEM) based counting method was developed to identify and classify fine dust on leaf and other material surfaces.

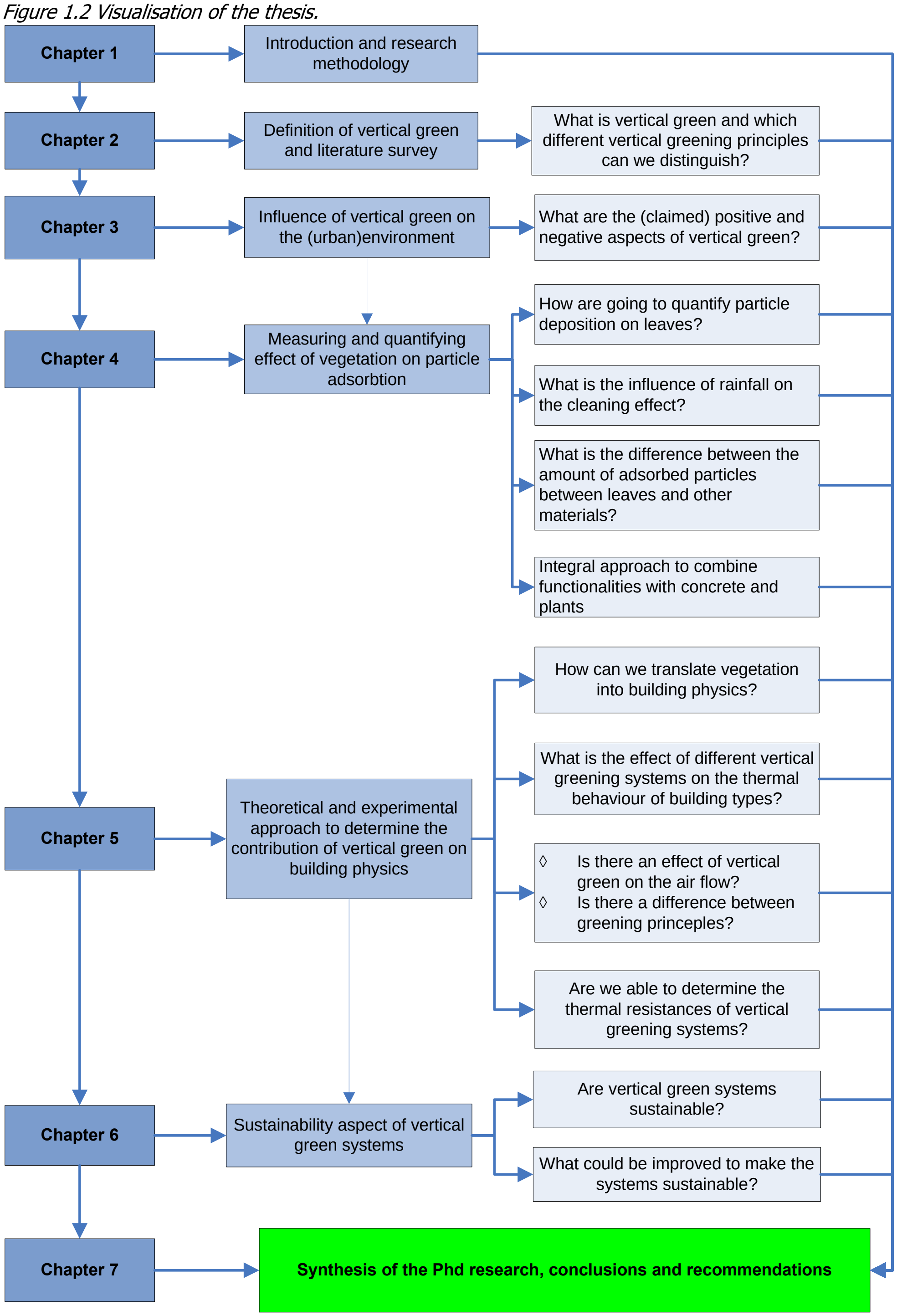
Chapter five presents a theoretical and experimental approach to quantify the thermal behaviour of vertical greening concepts and attempts to give valuable information about this topic for practice.

Chapter six attempts to investigate the sustainability of vertical greening concepts in relation with their benefits for the build environment, a life cycle analysis (LCA) was used to understand how vertical greening concepts could be improved to their environmental impact.

The thesis ends with chapter seven, which contains the conclusions, achievements and recommendations for further research and practice.

A visualisation of the research methodology of this thesis with relevant research questions per chapter is given in figure 1.2.

Figure 1.2 Visualisation of the thesis.



2 Vertical surfaces (façades, walls and noise barriers)

2.1 Introduction

A façade is part of the building and visible from the outside. Usually a façade is made of stone, concrete, glass, metal or wood. As definition of a façade can be found in the Van Dale dictionary of the Dutch language (2005): front wall of a building (originally the gable). In the building regulation 2003; a façade is defined as an external separation structure including the roof (VROM, 2003). The noise abatement act (February 16, 1979) gives as description for a façade: an Architectural structure that separates a room or building from the atmosphere, including the roof (VROM, 2007). In addition, in the vernacular, façades also refer to walls, sound barriers or other vertical erected surfaces.

In this doctoral thesis a façade will be considered as a structure that separates a building from the atmosphere as an integral part of a construction or as a freestanding structure (with a maximum inclination of 45 degrees from the horizontal axis). For example, a façade can have a slope and/or be curved, one can also think of the application as a noise barrier. A façade can form an ideal surface to be partly or fully covered by vegetation (Johnston et al., 2004). By applying vegetation on façades the natural values will be enhanced (Dunnet and Kingsbury, 2004). A façade can therefore be seen as a vertical garden and an extension of nature in ecological sense. One can then think of increasing the amenities of urban greenery and ecology in the urban area. A greened façade offers the possibility to take a different appearance in every season (e.g. changes in shape and colour intensity). The vertical garden gives in this way a natural shape (branches, leaves) and colour (changing of leaf cover) to a façade. Greening the façades can partly compensate the loss of green space by urban development. Planting façades will increase the amount of biomass production as well as taking up CO_2 inside cities. And lead to many positive effects on the habitat of humans and animals (Dunnet and Kingsbury, 2004, Köhler, 1993). The development and creation of vertical green in the urban environment can help to ensure that there is an increased amount of the habitats for a variety of plant and animal species. By integrating nature on façades (and roofs) additional green surfaces can be developed (which are attractive to birds, spiders, butterflies and other small insects).

Figure 2.1
A missed opportunity to green this sound barrier near the highway A15 with plants and to stimulate green and biodiversity in the built environment.

2.2 Overview of Vertical Green

Green façades, green walls, living walls, vertical green and vertical gardens are descriptive terms which are used to refer to all forms of vegetated wall surfaces. From the ground rooted traditional green façades and modern techniques to create green walls ensure that fundamental differences arise in vegetation types. Basically one can understand systems rooted into the ground and based on hydroponic systems (not rooted into the ground). Green wall technologies may be divided therefore into two major categories (figure 2.2) namely: rooted into the ground and rooted in artificial substrates or potting soil.

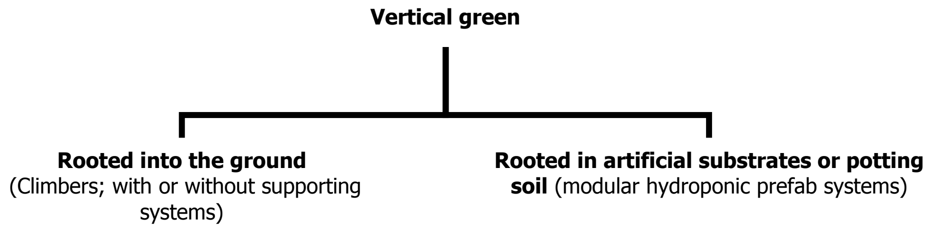


Figure 2.2 Basic distinctions between greening principles.

Both basic principles can be classified according to there application form in practice (table 2.1). Within the categories a distinction is made between; whether if the greening system uses the façade as guide to grow upwards (direct greening) or if the greening system and the façade are separated with an air cavity (indirect greening). The air space (cavity) between façade and greening system can be created by supporting systems, spacers, planter boxes or by modular substrate systems. Figure 2.3 shows differences between direct and indirect façade greening and possible forms of their application.

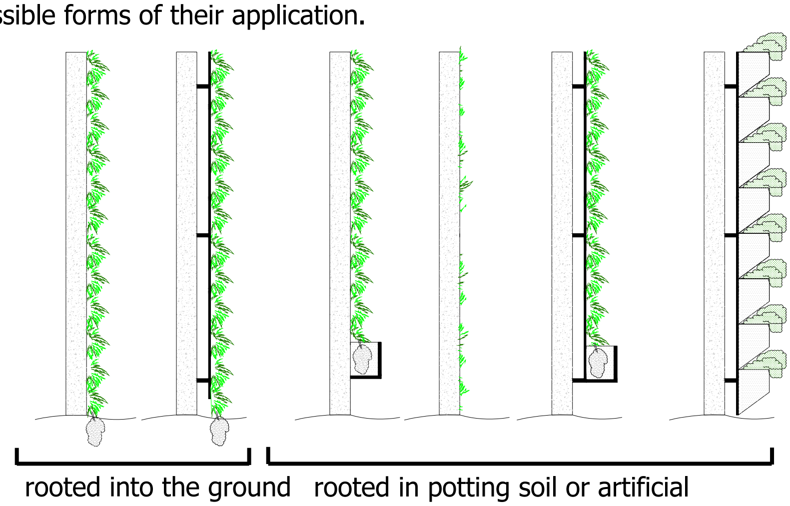


Figure 2.3 Rooted into the ground or rooted in artificial substrates (like mineral wool, foam, etc.) and potting soil; direct and indirect greening.

The systems that are based on the "artificial substrates and potting soil" principle are dependant on irrigation systems and adding nutrients to the substrate. Characteristic for this greening principle are the use of planter boxes filled with artificial substrate/potting soil or modular prefabricated panels equipped with artificial substrate and they are called Living Wall Systems (LWS). The used substrates and composition of living wall concepts can vary by manufacturer of the product. In general one can distinguish systems based on (figure 2.4):

1. Planter boxes
2. Foams
3. Laminar layers of felt sheets
4. Mineral wool

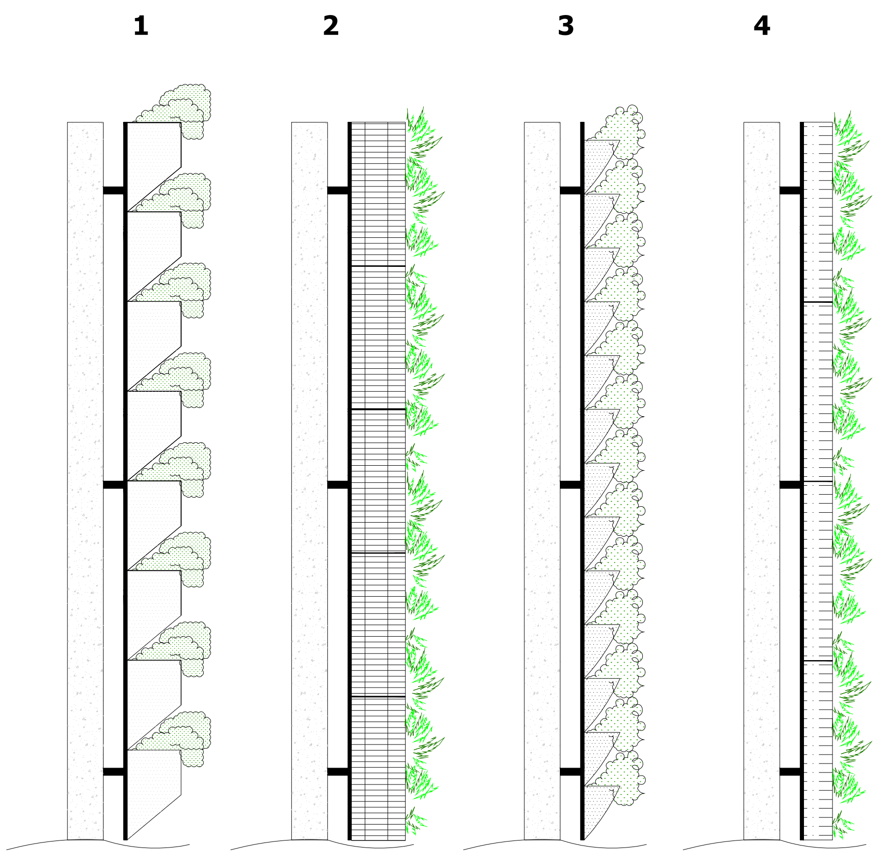
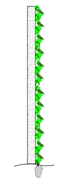
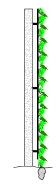
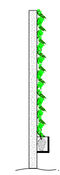
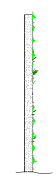
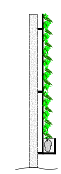
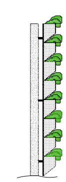


Figure 2.4 Typical configurations of LWS concepts.

Table 2.1 Classification of present vertical greening principles.

Green façade classification	**Vertical green**			
	Fixation principles against the façade	*Characteristic features*	*Plant types and systems*	
Rooted into the ground	**Direct** *(uses the façade as guide to grow upwards)*	Self climbing climbers	Aerial roots	
			Suckers	
	Indirect *(distance between climbing plant and façade via an supporting system or spacers)*	Self climbing climbers	Aerial roots	
			Suckers	
		Climbers with supporting system	Twining climbers	
			Tendril climbers	
			Scrambling climbers	
Rooted in artificial substrates and potting soil mixtures	**Direct** *(uses the façade as guide or as substrate to grow upwards)*	Self climbing climbers	Aerial roots	
			Suckers	
		Natural wall vegetation	Herbaceous plants and woody plants	
		Artificial created wall vegetation (grow able concrete)	Herbaceous plants	
	Indirect *(distance between climbing plant and façade via an supporting system, spacers, planter boxes or substrate which is used as guide to cover the façade).*	Climbers with supporting system	Twining climbers	
			Tendril climbers	
			Scrambling climbers	
		Living wall systems (LWS)	Herbaceous plants and/or woody plants	

2.3 Vertical green; an historical view

The technology to green our cities is not a new phenomenon, the first description of greening our inner city goes back to the seventh century B.C. with the hanging gardens of Babylon. The gardens of Babylon were built by King Nebuchadnezzar for his wife Amyitis. Nebuchadnezzar ordered artificial knolls, hills, and watercourses planted with exotic trees, shrubs, and trailing vines, all this effort to make his queen Amyitis less homesick for her native well greened country Persia (Polinger, 1998). The most famous Mesopotamian gardens of Babylon are considered as one of the seven wonders of the ancient world.

Figure 2.5 Hanging Gardens of Babylon situated by Maarten van Heemskerck in the 16th century.

Vertical and horizontal gardens were also known in the Roman Empire, for example shopkeepers in the city Pompeii grew their vines on the balconies of the shops (Peck et al., 1999). In the Renaissance (14th-16th century) fruit walls formed a real craze among European estate owners and monastery gardens. Estate owners gathered fanatic new or exotic fruits which they personally prune against the façades; the warm sheltered façades formed a perfect habitat for the growing process. Between 1650 and 1830 fruit walls were extremely popular, with the highlight of the construction of the palace gardens of Louis XIV at Versailles about 1680 (Robles, 2004).

Figure 2.6 Fruitwall at Zuylen castle (Zuylen Castle).

In Scandinavia in the past, roofs were covered with a soil layer (sod) that was stripped from surrounding grass meadows. Underneath the sod structurally heavy timber beams were interspaced with birch bark to act as a waterproofing layer. In warmer climates it helps to keep the heat out of the building and in colder climates it helps retaining heat inside the building (Peck et al., 1999).

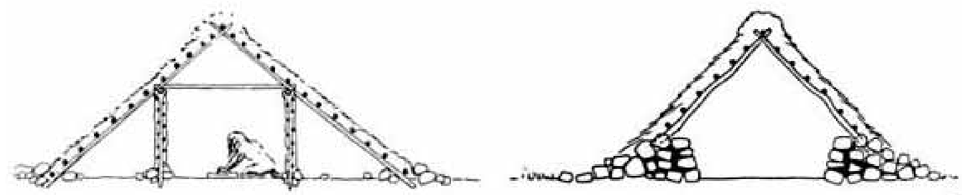


Figure 2.7 The first green roofs, timber beams covered with sod (Marian C. Donnelly, 1992.).

Figure 2.8 Modern version of a (Sedum planted) green roof. (Texel, The Netherlands.)

Since the beginning of 17th and 18th century North American plants such as Virginia creeper (*Parthenocissus quinquefolia*), the German trumpet climber (*Campsis*) and the Dutch pipe (*Aristolochia)* were brought to Europe. Over the centuries, various techniques were used to let grow plants along façades and walls, but the creation of vertical green became especially possible because people obtained plants from the solid ground and put them into planter boxes (Lambertini, 2007). The Paul-Lincke-Ufer (PLU) project in the neighbourhood of Kreuzberg (Berlin) was the first inner-city residential eco-project (Köhler, 2006). The project started in 1984 to examine the potential of inner-city greening, the façade was greened with ivy and virginia creeper planted in flower pots along the façade and at planted at the base of the façade (Peters, 2011).
Bringing nature under the interest of city dwellers was one of the characteristics of the famous artist and architect Friedensreich Hundertwasser. Hundertwasser designed in 1986, an accommodation complex of 52 houses with undulating

façades and roofs. More than 200 trees and shrubs are growing on the roof, from the balconies and planter boxes (Lambertini, 2007). The Hundertwasser House in Vienna (Figure 2.9) is an example where the architect tried to green the building and bring green more among the people. Hundertwasser introduced to the public a wider notion of green architecture as the symbiotic integration of plant life and building. Green(ness) became and was part of a new experimental way of life, Hundertwasser felt that people were entitled to their own creativity into their home and commitment and that straight lines do not belong to this concept (Lambertini, 2007). Also in denser urban areas a question arises for more greenness by the increase of traffic and therefore air pollution (Lambertini, 2007). In large cities it is cumbersome to create green areas because the cities are already built up and there is a lack on "free" space (Lambertini, 2007). Ebenezer Howard was an inspiration source for many people with his garden cities concept beginning 1900 in the United Kingdom. In the beginning of the seventies a new movement was developed and called "green architecture", which was an imitation of the ideas of Frank Loyd Wright and stood in strong contrast with the modern developments in that time. Centrally inside this movement of architecture was that the focus stood on ecological aspects within the cities (Lambertini, 2007).
Beside for architectural reasons people became increasingly aware that green is indispensable in the urban environment. Therefore in the 19th century in many European cities, woody climbers were frequently used as a cover for simple façades. In Germany incentive programmes were developed for green in the city in the beginning of 1980 (Köhler, 2008).

One of the first living wall concepts (hydroponic) on a large scale was created in the 1930s by a cooperation of well known architects as Burle Marx, Lucio Costa and Le Corbusier. They designed and created a hanging garden for the Ministry of health and education in Rio de Janeiro where the gardens had no access to natural soil (Lambertini, 2007). At the present (21st century), the green building envelope is again under the interest to bring nature back in our dense urban areas. A growing interest in environmental issues forms a base for integral solutions; combining nature and a technical approach to make use of the multiple benefits of green. These multiple benefits (habitat creation, biodiversity, cooling and insulation properties, adsorbing fine dust, etc.) form a component of current urban design (Köhler, 2008).

Figure 2.9 Hundertwasser House in Vienna (pixdaus).

The green building technology as we consider nowadays is the modern version of the ancient greening principles. The green building envelope makes use of the benefits of nature in a technical manner broader than only the use of green roofs and green façades. Green building is defined by the Office of the Federal Environmental Executive as "the practice of:

- Increasing the efficiency with which buildings and their sites use energy, water, and materials;
- By reducing building impacts of human health and the environment, through better siting, design, construction, operation, maintenance, and removal throughout the complete life cycle.

Greening buildings with vegetation and making use of the benefits of vegetation (examples: air quality improvements, increased biodiversity, insulation properties, mitigation of heat inside as well as outside of buildings) fits in the definition of green building technologies.

Merging art, engineering and botany will create new uses for plants outside their natural habitat, and allowed architects and engineers to construct vertical gardens for the threefold purpose of aesthetics, technology and ecology.

2.4 Definition of Vertical Green

Vertical gardens or green façades can be seen as a living cladding system attached to the building structure. Strategies for the development of living walls include: planting in the ground, at grade (i.e. planting in planter boxes attached to walls, on window reveals, balcony rails or as part of horizontal and vertical sun screens over windows, doors and glazed areas); and planting in a vertical hydroponic system (Peck et al., 1999).

The term vertical garden is used to define the growing of plants on, up, or against the façade of a building. Strategies for vertical garden development include: planting in the ground; at grade; planting in planter boxes (at grade, attached to walls, on window ledges, balcony rails). Dunnet and Kingsbury (2004) describe façade greening as a living and therefore a self-regenerating cladding system for buildings, with the traditional use of climbing plants to cover the surface of a building. Green façades can be created by the use of climbing plants directly at the façade or with the assistance of a supporting system (indirectly) to create a space between façade and the plant structure according to (Krusche et al., 1982).

Another definition of greened façades is given by Hermy (2005); green façades are the green cover on vertical surfaces by plants rooted in soil. This can be rooted in the soil at ground level of the façade as well as in planter boxes possibly placed on the building. In German literature greened façades are typically classified as climbing plants planted against a façade. Köhler (1993) describe this as:

Green façade = building + climbing plant

A more recent definition of greened façades given by Köhler (2008) is as follows: green or greened façades as typically covered with woody or herbaceous climbers either planted into the ground or in planter boxes in order to cover buildings with vegetation. 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. LWS can be used outside a building as well as inside a building.

There are several different terms used in literature to discuss vegetated vertical building surfaces. As definition of vertical green in this document will be used:

"Vertical green is the result of greening vertical surfaces with plants, either rooted into the ground, in the wall material itself or in planter boxes attached to the wall in order to cover buildings with vegetation."

Supporting systems are sometimes necessary and planter boxes (such as prefabricated systems (living wall systems) attached to walls can require artificial mixtures of growing media to facilitate plant growth. Supplemental irrigation or hydroponic systems are necessary for the planter boxes and living wall concepts.

2.5 Classification of climbing (plant) types used for façade greening

In order to cover façades with climbing plants it is important to understand the basic principles that climbing plants use to climb and the ways to support them if necessary. Climbers can be classified into the following categories according to their climbing pattern (Dunnet and Kingsbury, 2004):

True climbers with methods of attachment to supports
- Self clinging climbers
  - Climbers with aerial roots
  - Climbers with suckers
- Twining climbers
- Climbers with specialized leaves for attachment, such as tendrils

Self supporting woody plants trained as wall shrubs
- Ramblers or scramblers

The Forschungsgesellschaft Landschaftentwicklung Landschaftsbau (FLL) summarizes the term climbing plants to all type of plants that need support for an up going growth (figure 2.10). The botanical classification is divided into two groups of plants:

1. self clinging plants
2. climbers that need support

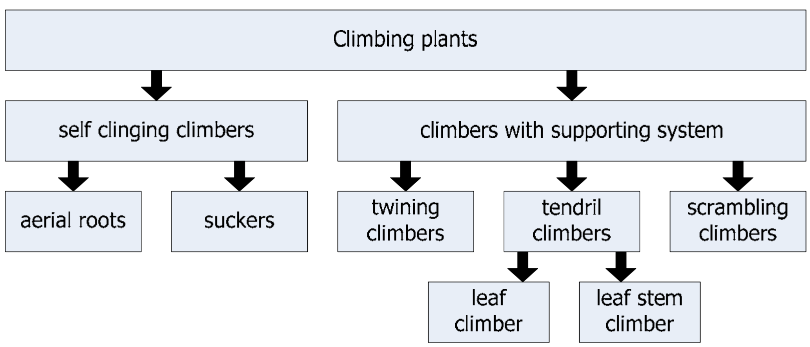


Figure 2.10 Classification of climbing plants according to FLL 2000.

Self clinging climbers

Self clinging plants have a strong tendency to grow upwards towards the light (phototropism). Climbers with aerial roots (for example common ivy (*Hedera helix*)) or climbers with suckers (for example Boston ivy (*Parthenocissus*)) need no additional help (supporting system) to grow against a façade. The surface of the façade should preferably be as rough as the tree trunks or rock on which these plants grow naturally. Many plants with aerial roots or suckers attach themselves so well that they find guidance on a concrete, brick, render or cementious wall (the surface must have enough roughness for their microscopic root hairs to grab on). Smooth or shiny metal, glass and plastic surfaces are in theory not suitable (Dunnet and Kingsbury, 2004). Timber as cladding material isn't advisable because of the joints between planks (Hiemstra et al., 2004). Joints are vulnerable for the penetration of aerial roots and twigs due to the negative phototropism (they grow away from the light). Self clinging climbers as for example *Hedera helix* can easily reach 30 m with a cover surface of 600 m^2 (Dunnet and Kingsbury, 2004). In order to cover façades one can choose for deciduous or evergreen climbing species.

Figure 2.11 Aerial roots of Common ivy (Hedera helix) on wood and masonry.

Figure 2.12 Detail of a sucker climber the Boston ivy (Parthenocissus) and a complete façade covered with Boston ivy.

Twining climbers

Twining plants form the largest group under the climbing plants. The main stem and/or side stem twist itself with a helical motion around wires or other supporting systems. The supporting systems are usually placed with a distance from the façade. The required distance between the façade and the twisting climbing plant depends on the growth of the branch that is expected (Hiemstra et al., 2004). The growing direction is mainly vertically which is important for placement of supporting systems. Some species of the twining climbers (for example wisteria) can reach a height of 30 m.

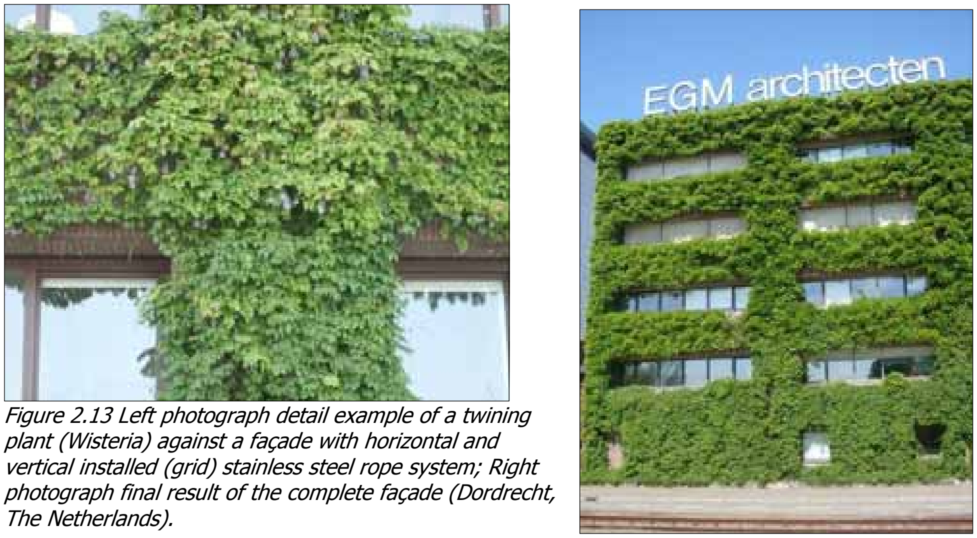


Figure 2.13 Left photograph detail example of a twining plant (Wisteria) against a façade with horizontal and vertical installed (grid) stainless steel rope system; Right photograph final result of the complete façade (Dordrecht, The Netherlands).

Figure 2.14 Example of twining plants (Aristolochia and Wisteria) against a façade using a vertical stainless steel rope system (Berlin, Germany).

Tendril and leaf twining climbers

These plants have tendrils; specialized (leaf) stems that can twist like a corkscrew to wrap around a climbing support (for example *Vitis* species). The tendrils can last for several years but eventually die (Dunnet and Kingsbury, 2004). As supporting system different types can be used like: wires, a grid, rods or slats can be used (trellis type). The supporting systems can be placed both horizontally and vertically without problems for the plants to grow upwards (Hiemstra et al., 2004). Leaf twining climbers (primarily clematis) depend upon leaf stems, nearly always deciduous, to hold on.

Figure 2.15 Example of a leaf-stem (Clematis) climber as twining plant against a façade during winter period and during summer period (right photograph Jan Legtenberg).

Ramblers

These plants are growing by weaving through a supporting system, where they hook with thorns or spines. They grow like a veil over other structures than they really climb. These types of plants tend to grow three-dimensional, and need often human intervention to be held flat against the façade. This intervention however requires maintenance and thus are extra costs involved to green a façade (Hiemstra et al., 2004). The best known examples of ramblers are the climbing rose and the winter jasmine.

Figure 2.16 Example of rambler (climbing rose) against a façade (photo fransprins).

3 Vertical Green and its environmental impact

3.1 Introduction

Greening of outside walls or façades of buildings gets more interest in recent years. In recent decades living walls, the vertical greening of façades of buildings or noise barriers have been realized. Vertical gardens or living wall concepts offer numerous economic, social and environmental benefits such as greenhouse gas reduction, adaptation to climate change, air quality improvements, habitat provision and improved aesthetics, whereas a lot of these benefits are claimed or not well investigated yet. Despite these benefits a widespread market penetration of green façades over the world or the use of these greening technologies remains in its infancy.

Façades can form an ideal substrate for partial or complete vegetation of several plant species. By allowing and encouraging plants to grow on walls the natural environment is being extended into urban areas; the natural habitats of cliff and rock slopes are simulated by brick and concrete (Johnston et al., 2004). A façade can be considered as a vertical garden and as an extension of nature in a ecological sense. Greening the exterior of buildings will provide ecological services like breeding and resting habitats for birds which may be enjoyed by humans. A well vegetated façade offers in each season the possibility of the transformation of the visual aspects (i.e. for example: changes in colour intensities of the leaves), on this way a green façade is always renewing.

In recent years different systems (figure 2.3) have been developed, such as greening the façade directly or indirectly and greening possibilities incorporated within the construction of the wall (Köhler, 2008). Despite the range of possibilities there is still great hesitation in the building sector (from the policy makers, the designer, the architect until the builder and the user) to increase the amount of outdoor wall greening. Apparently mainly due to the possible disadvantages: the need for extra maintenance, falling of leaves, chance of damaging the wall structure, increase of the amount of insects and spiders in the house or the unexpected extra costs involved.

There is a widespread belief that plants are harmful to building structures, ripping out mortar and prising apart joints with their roots (Johnston et al., 2004). The evidence suggests that these problems have been greatly exaggerated, except where decay has already started and plants can accelerate the process of deterioration by the growing process of roots (Johnston et al., 2004). In reality there is little evidence that plants damage walls. In most cases the exact opposite is true, a plant cover will protect the wall from the elements. Ancient walls still stand, despite centuries of plant growth (Dunnet and Kingsbury, 2004; Johnston et al., 2004; Maes, 1993).

Vegetation can be seen as an additive (construction) material to increase the (multi)functionality of façades or buildings. Greening the cities is not a new approach (i.e. hanging gardens of Babylon), but it is rarely investigated. Also the possibility to let grow vegetation on the exterior of building (materials) is a wide field to investigate.

Figure 3.1a Left: rooted into the ground directly against the façade, 3.1b Right: rooted into the ground indirectly against the façade (photo Hoek hoveniers).

Figure 3.2a Left: Prefab growing system or living wall system created by Patrick Blanck (Berlin, Germany). 3.2b Right photo: Also artificial growing substrate panels; living wall concept of Cultilene Saint Gobain.

Figure 3.3a Left: not rooted into the ground; indirectly against the façade (Monaco). 3.3b Right photo: Detail of a planter boxes system against façade (photos Huib Sneep).

Figure 3.4a Characteristic wall vegetation typically on older constructions created with limestone mortar joints.

Figure 3.4b Porous concrete intended as growing medium for plants and to stimulate the colonization of different plant species.

In table 3.1 a general overview is given about the advantages and disadvantages of green walls in general based on the literature (Dunnet and Kingsbury, 2004; Krusche et al., 1982; Minke, 1982, Köhler, 1993; Peck et al., 1999; Johnston et al., 2004). The table is based on the different greening systems according to literature.

Table 3.1 Advantages and disadvantages of green walls based on literature review.

Vertical greening type	*Advantages*	*Disadvantages*
Direct façade greening	• low planting costs • suitable for retrofit projects • relatively little technical expertise needed • increased biodiversity development • breeding and nesting possibilities • no need for irrigation systems • reduction of indoor and outdoor temperature due to evatranspiration and shadowing • conversion of air polluting substances (CO_2, NO_X and SO_2) • adsorption of particulate matter (PM_x) on leaves. • improved aesthetic value	• chance on moisture problems (constructions without a cavity wall) • maintenance costs • not suitable for each construction • long growing period to get result • maximum greening height of +/- 25 meters.
Indirect façade greening	• no direct contact of vegetation with façade • suitable for retrofitting projects • possibility to green older constructions (a nine-inch wall) without change on moisture problems. • increased biodiversity development • breeding and nesting possibilities • no need for irrigation systems • reduction of indoor and outdoor temperature due to evatranspiration and shadowing • conversion of air polluting substances (CO_2, NO_X and SO_2) • adsorption of particulate matter (PM_x) on leaves. • improved aesthetic value	• maintenance costs • long growing period to get result • maximum greening height of +/- 25 meters.
Wall vegetation	• development of vegetation spontaneously • natural effect • inexpensive • increased biodiversity development • no need for irrigation systems • conversion of air polluting substances (CO_2, NO_X and SO_2) • adsorption of particulate matter (PM_x) on leaves.	• can be unattractive due to backlog idea • not suitable for each construction material (growing possibility or damaging effects).

It should be noted that the advantages and disadvantages described in table 3.1 provide generic information only. Each individual green façade system will depend on different factors such as (Peck et al., 1999):

- budget
- location
- structural capacity of the building
- historical value of a building (monuments)

3.2 General introduction concerning air polluting substances

3.2.1 Particulate matter (PM_x)

Particulate matter in the atmosphere is one of the greatest threats to the human health. It causes heart diseases and/or aggravates acute respiratory diseases. Researchers of the Dutch National Institute for Public Health and the Environment (RIVM) and the Environmental Assessment Agency (MNP) have estimated that each year approximately 18.000 of people die prematurely rather by short-term exhibition to fine particles (PM_x). It concerns especially elderly and people with heart, cardiovascular or lung diseases (MNP and RIVM, 2005).

Particulate matter are all suspended particles in the atmosphere smaller than 10 micrometers. Particulate matter is a particle-like contamination and one of the most harmful aspects of air pollution. It is a mixture of particles that differ in origin and properties. Particulate matter consists of: soot, soil dust, combustion exhaust, sea salt, plant material, spores and pollen (Weijers et al., 2001). Depending on the diameter of the particles it refers to PM_{10} (10 micrometers) or $PM_{2.5}$ (2.5 micrometers). The smallest particles are the most dangerous for health. In general, the smaller the particles, the deeper they penetrate into the respiratory system were it is taken up into the blood. This is because they can be deeply inhaled. In this way, respiratory and/or cardiovascular disease arise (Pekkanen et al., 2000). Exposure to fine particulate air pollution has been associated with increased morbidity and mortality. Research done by Pope et al (2009) shows an increased life expectancy associated with differential decrease in fine dust concentrations that occurred during the 1980s and 1990s in the United States. This research shows the impact of fine dust inhalation by humans and the need to decrease the air pollution.

Due to the small particle size particulate matter can be moved over large distances in the air and it can be seen as a cross-border problem. To improve the air quality at European level so-called framework directives with associated daughter directives has been established. In one of the directives so-called marginal values (table 3.2) have been established for the particulate matter quality. It is required that the particulate matter quality no longer than 35 days per year can exceed the daily average of 50 µg/m^3 and a year average amount not more than 40 µg/m^3. The marginal values for particulate matter in the Netherlands are regularly exceeded. Exceeding the daily average is in a number of places in the Netherlands a problem (RIVM).

Table 3.2 Marginal values daily averages for particulate matter (PM_{10}) in the Netherlands (MNP, 2008).

Duration	Particulate matter quantity
maximum 35 days	50 µg/m^3
maximum year average	40 µg/m^3

The amount of particulate matter in the air depends on the local climatological conditions. Particulate matter for example can be quickly spread by the wind so that exceeding the threshold value will not occur. In addition, rain or fog can adsorb particulate matter out of the air and reduce the concentration.

Particulate matter can be classified in particles from a natural or anthropogenic origin. Anthropogenic particulate matter comes from human activities. Particulate matter is i.e. created by combustion processes but also include wear on tires and road by traffic. Industry and traffic are the main source of anthropogenic particulate matter (MNP and RIVM, 2005). In addition the construction and agricultural sector are important sources but also households can contribute to the emissions of fine particles in the immediate area (MNP and RIVM, 2005). Fine dust particles can be primary or secondary:

- Primary particulate matter: results from friction processes (e.g. car engines and brakes of cars), by the combustion of fossil fuels. Another often underestimated natural source of particulate matter are spores and pollen emitted by plants and fungi.
- Secondary particulate matter: results from chemical reactions of gases such as ammonia (NH_3), sulphur dioxide (SO_2) and nitrogen oxides (NO_x). Also organic compounds can form secondary particulate matter. The fine dust particles can be created by nucleation (the formation of new particles) or by coagulation (adhesion to existing particles) Bloemen et al., 1998, Figure 3.5.

Particle size and mass

Particles are divided into groups according to their size. The groups are expressed according to their size in micrometer and measuring the maximum aerodynamic diameter of a spherical particle moving in the air as a dust particle. The notation for the groups is PM_x and stands for particulate matter. Particles larger than $PM_{2.5}$ are mainly mechanically formed. Particles smaller than $PM_{2.5}$ arise mainly from condensation of combustion products or by secondary aerosols

The marginal values are dealing with the particle mass concentration in the air. However the particle mass, when it is expressed as PM_{10} or $PM_{2,5}$ is not a suitable indicator for health risk, because these fractions include particles of a very different physical nature and chemical content. Beside this a strong correlation has been found with the amount of particles and health effects. Especially the health effects for insoluble particles within the ultrafine size fraction correlates fairly with the magnitude of its surface (MNP and RIVM, 2005).

Table 3.2 Classification of particulate matter with accompanying group names and particle sizes.

Particle size	Group name	Aerodynamic diameter
TSP	total suspended particles	≤ 100 micron
PM_{10}	coarse	≤ 10 micron
$PM_{10-2.5}$	fine	≥ 2.5 micron ≤ 10 micron
$PM_{0.1}$	ultrafine	≤ 0.1 micron

The size of the particles (aerodynamic diameter) determines its behaviour in the air. The smallest particles stay in the air for days before they precipitate or deposit on a surface.

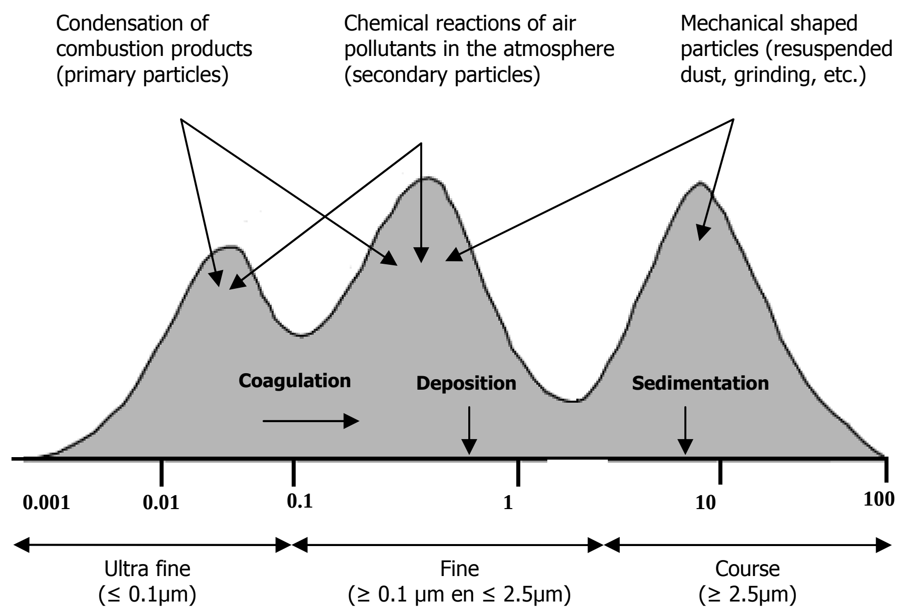


Figure 3.5 Simplified representation of particle size distribution of particles in the atmosphere and the main processes of the emergence and disappearance of particles (Bloemen et al., 1998).

3.2.2 Carbon dioxide (CO_2)

Carbon dioxide (CO_2) is a gaseous compound which is released mainly due to the combustion of fossil fuels. Natural sources for the emission of carbon dioxide are among other things savannas and bunch fires or the emission of volcanoes. But also the metabolism of people and animals produces an emission of carbon dioxide. Since the industrial revolution the share of carbon dioxide has increased strongly in the atmosphere. The quantity of carbon dioxide produced by the combustion of fossil fuels is extremely increased. This increase is not compensated by an equal commitment by for example plants and algae. Dry air contains by volume roughly: 78.09% nitrogen (N_2), 20.95% oxygen (O_2), 0.93% argon (Ar) and 0.039% carbon dioxide (CO_2). The increase of the carbon content is considered as one of the key factors for the warming (greenhouse effect) up of the earth. Strictly speaking carbon dioxide is no polluting substance for humans and animals; it is not harmful for health and is eventually in the breath of humans and animals naturally. Plants use carbon dioxide in their growing process (photosynthesis), carbon dioxide is taken out of the air by the stomata and in the form of glucose it is fixed in the plant. At the end of the photosynthesis reaction oxygen is released (O_2) to the surrounding air.

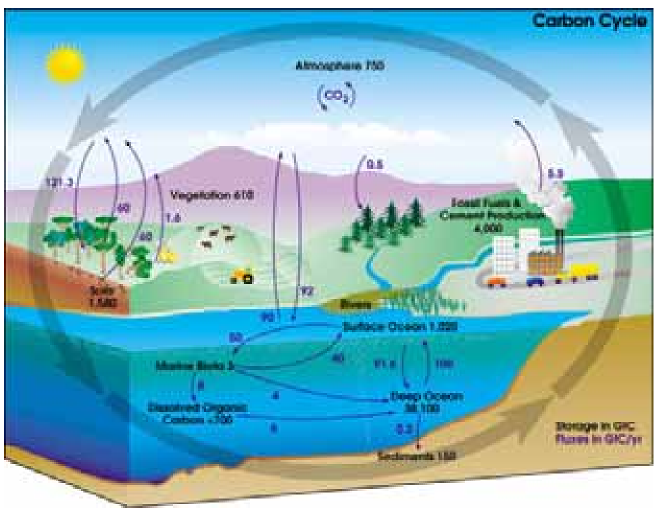


Figure 3.6 Schematization of (long and short) carbon cycle (http://earthobservatory.nasa.gov/Library/CarbonCycle/carbon_cycle4.html

The carbon cycle is the biogeochemical cycle by which carbon is exchanged among the biosphere, pedosphere, geosphere, hydrosphere, and atmosphere of the Earth. The carbon cycle can be divided into two categories namely:

- Long-term carbon (carbon that is fixed in fossil fuels such as natural gas, coal and oil. Formation of fossil fuels occurred under heat and pressure in the earth's crust over millions of years).
- Short-term carbon (carbon that is fixed in plant material and for example in the tissue of humans and animals).

Using fossil (long term carbon) fuels as earlier mentioned will lead to higher amounts of carbon dioxides in the atmosphere and thus results in an increase (4% of the total increase) of the CO_2 in the air. Fossil fuels are non-renewable resources because they take millions of years to form, and reserves are being depleted much faster than new ones are being made. The use of biomass (short term carbon) for energy production, will also lead to the release of CO_2 in the atmosphere. However this is carbon that was fixed by plants and does not contribute to an increase of the greenhouse gas concentrations. Biomass is a renewable resource due to the short time of formation.

3.2.3 Acidifying substances

Under acidifying substances one understands among other things: nitrogen oxides (NO_x), sulphur dioxide (SO_2), ammonia (NH_3) and volatile organic compounds (VOC's). These acidifying substances arrive by air or water (dry or wet deposition) in the soil.
Nitrogen oxide (NO_x) is the collective name for compounds between oxygen (O_2) and nitrogen (N_2). Nitrogen oxides are a result from burning fossil fuels, but also in any other conceivable combustion process commit themselves to nitrogen oxides. This creates nitrogen dioxide (NO_2) by a side reaction in the combustion engine because in the natural open air present nitrogen and oxygen react. The higher the temperature, the easier those compounds will be created. Acidification of soil or water is a result of the emission of polluting gases (SO_2, NO_x and NH_3). The emergence of environmentally harmful "acid rain" occurs when nitrogen bind with water, the reaction results in nitric acid (HNO_3). The harmful ozone (O_3) (global warming and smog formation) can be formed when nitrogen oxides (NO_x) and volatile organic compounds (VOC) react chemically under the influence of sunlight.

Also sulphur dioxide (SO_2) is generated in the combustion process of fossil fuels. Sulphur dioxide in air with the presence of moisture and other compounds readily form sulphur trioxide (SO_3). Sulphur is a compound from which in water sulphuric acid (H_2SO_4) will form.

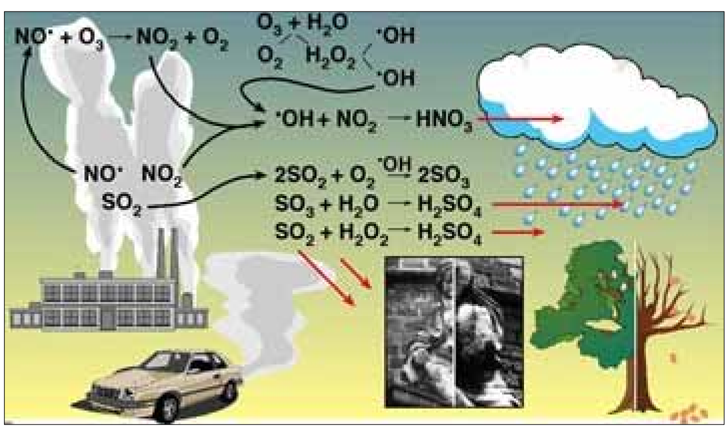


Figure 3.7 Acidifying compounds in the atmosphere and their formations (wetenschapsforum).

Ammonia (NH_3) is mainly originating from intensive cattle farming. In areas with agrarian sources the ammonia is mainly ejected at low altitude. In combination with the high deposition rate it ensures that much ammonia is deposited close to the source. In these (rural) areas ammonia (NH_3) is therefore responsible to the high contribution of nitrogen deposition (N).

3.3 Current methods to reduce atmospheric pollution

3.3.1 Catalytically processes

Through the use of a catalyst, the amount of polluting substances can be reduced. A catalyst is a substance that can speed up or slow down a reaction. Unlike other compounds that participate in a chemical reaction, a catalyst is not consumed by the reaction itself. Catalysts which are suitable to reduce the amount of carbon dioxide, nitrogen oxides and particulate matter are for example the minerals zeolite and dolomite.
Also titanium dioxide (TiO_2) appears to be a functional catalyst which can reduce pollutants. Titanium dioxide is a so called photo catalyst under ultraviolet (UV) light. Especially the nitrogen oxides (NO_x) can be reduced by titanium dioxide. Titanium dioxide converts NO_x into nitrate (NO_3). In urban areas there is an important additional factor, namely the formation of smog. The photochemical smog is formed by reactions caused by the action of sunlight on NO_2 and VOC's to form ozone (Beeldens, 2008). Another consequence of the pollution is the creation of acid rain, when the NO_x oxidized in air to NO_3.

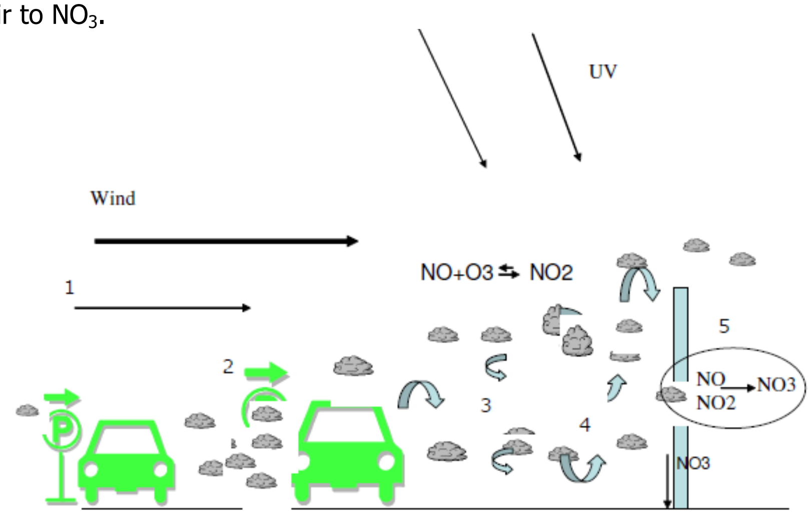


Figure 3.8 Basic principle of titanium dioxide as a catalyst (IPL, 2009).

When using a photo catalytic active material such as titanium dioxide (TiO_2), it should be present at the surface and accessible to light and air pollutants. Some parameters are therefore very important, accessibility for the (sun) light, contact with the air and turbulence in the height of the photo catalytic surface

(Beeldens, 2008). This will greatly increase the contact time and consequently the conversion benefit related to the oxidation process. The oxidation product is then washed away with rainwater into the soil or sewer.

A possible application for the oxidation product is to use it as fertilizer for plants. On this way an integration of functions will be used. The plants therefore can use the released nitrogen as an important element for their growth.

3.3.2 Electrical precipitation

In the atmosphere there are both positive and negatively charged ions. Ions are electrically charged particles. They arise from a molecule or an atom when a negatively charged particle (electron) is added or taken away. This process is called ionization (RIVM, 2010). Several positive and negative ions can be formed in the air for example: nitrate (NO_3^-), sulphate (SO_4^{2-}), fluoride (F^-) and chloride (Cl^-). In general there are more positive than negative ions in the atmosphere. Positive ions mainly arise by movement and/or friction processes (Anthropogenic (man-made) particles from combustion processes are also frequently charged). Negative particles in the atmosphere collide with the positive particles which they neutralized. In polluted air (with dust and smoke for example) the negative ions are consumed and therefore in the minority this results in an unhealthy climate.
The principle of electrostatic precipitation can be divided into active and passive deposition of (fine) dust particles. Active electrostatic precipitation can be described by a process were fine particles are guided between charged electrodes (they pass through an electric field). In this way fine dust is positively electrically charged and can be scavenged. For passive precipitation usually a plastic filter material is used, by keeping a constant flow of air or liquid the filter material obtained a natural electrical charge.

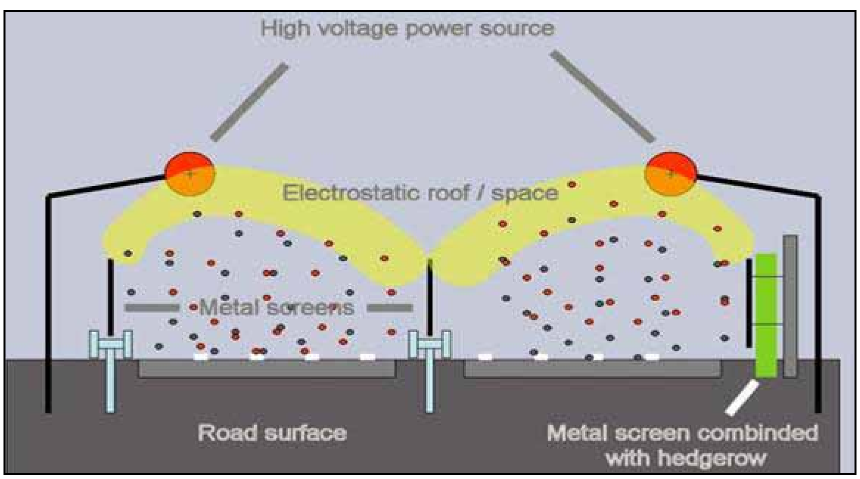


Figure 3.9 Schematization of electrostatic precipitation (W.J.N. Ursem/BAM).

3.3.3 Vegetation

The surfaces of vegetation provide a major adsorption surface in contact with the atmosphere (Smith, 1976). The capability of plants to interact with air contaminants is commonly reviewed in literature (Smith, 1976; Minke, 1982; Krusche et al., 1982; Bartfelder and Köhler, 1987; Fowler, 1989; Thönessen, 2002; Tonneijck et al., 2002; Beckett et al., 2004; Sternberg et al., 2010). Vegetation can serve to reduce the amount of air pollutants (CO_2, NO_x, PM_X and VOC's) from the air. It is known from biology that plants and algae through photosynthesis adsorb air pollutants for plant growth. Adsorbing (gas exchange) of pollutants such as carbon dioxide and nitrogen oxides happens by means of the stomata located in the leaf surface. Plant species with many active stomata per unit leaf area absorb a relatively large amount of gaseous pollutants (CO_2, SO_2, NO_x) from the air. In general plants with broad and thin leaves are more effective. Therefore leaves of deciduous trees are more effective for gaseous absorption than for example conifer needles (IPL, 2006).

The basic principles for particle deposition on natural surfaces can be described by three processes: sedimentation under the influence of gravity, impaction and deposition under the influence of precipitation (Smith, 1976). Interception and retention of (fine) particles takes place on all above ground situated parts of vegetation. Sedimentation usually results in deposition on the upper side of leaf surfaces (Smith, 1976). In general, the hairy and the rougher the leaf surface is, the more fine particles can be adsorbed. Particulate matter also attaches to more sticky or moist leaf surfaces (Tonneijck and Blom-Zandstra, 2002; Wesseling et al., 2004). Also the electrical charge of the vegetation and particles has an influence on the capture of fine dust by plants (Oosterbaan et al., 2006). The contact between pollution and leaves is essential for the filtering properties of plants. As wind passes around a plant, the airflow separates and moves around the plant, while the momentum of the particle forces it to impact with and remain on the plant surface. The efficiency of collection via impaction increases with decreasing diameter of the plant part and increasing diameter of the particles (Smith and Dochinger, 1976). Vegetation can be a temporary site for particulates as they can be re-suspended (resuspention of 50% is estimated by Nowak et al., 1994) into the atmosphere by wind turbulence or washed off by rain to the subsoil (Wesely, 1989).

Research done by ES Consulting showed that an effective planting of vegetation can reduce 20% of the fine dust concentration in the air (Steltman, 2005). This means that vegetation can have only a "small" scale effect on the fine dust concentration in the air, but is eventually better than taking no action. One have to taken into account that the benefit of vegetation is probably under estimated by omitting indirect relations caused by the application of urban green. Indirect side effects are for example that due to the insulating properties of green façades and green roofs the amount (and demand) of energy used for both cooling and heating in buildings could be lowered. On a larger scale this would also lead to a reduction of combustion products by the electricity plants (coal or wood fired). As other example can be used that due to greening of the building envelope lower ambient temperatures could be reached due to evapotranspiration of plants. Lower ambient temperatures in urban areas affect the smog formation process. Although smog formation is a complex process, it is caused by a photochemical reaction that is accelerated under higher (air) temperatures. Cooler air by evapotranspiration of water by plants reduces the reaction rate and hence the formation of smog (Currie and Bass, 2008).

3.4 The general benefits of vertical green

3.4.1 Air quality improvement

Leaves of plants provides a large surface area which is capable of filtering out particulate matter (PM_x) and other pollutants such as NO_x (conversion to nitrate (NO_3^-) and nitrite (NO_2^-)) and CO_2 in daytime. A green façade will block the movement of particulate matter particles along the side of a building and filter them (Minke et al., 1982). Vegetation has a large collecting surface area and promotes also vertical transport by enhancing turbulence (Fowler et al., 2001). When concrete, brick, stone, glass and asphalt surfaces are heated during the summer period, vertical thermal air movements (upwards) are created and dust particles found on the ground are carried and spread into the air (Minke et al., 1982). Particulate matter is adsorbed by the leaves, trunks and twigs and is an efficient sink for particulate matter (Fowler et al., 1989). According to Hosker and Lindberg (1982) fine dust ($PM_{2.5}$ and PM_{10}) concentrations are reduced when particles are adhered to the leaves and stems of plants. Literature claims that by rainfall the adsorbed particulate matter is washed off into the soil or substrate below. However results from a conducted simulated rainfall experiment (paragraph 4.4 of this thesis), shows that especially the fine and ultra fine particles are fixed on the leaf surface. Also falling of leaves in autumn contributes to particle binding. Research shows for example that plant barriers immediately along a roadside (daily traffic level 20.000-50.000 vehicles) are more beneficial in capturing lead (Pb) and cadmium (Cd) particles than plants investigated in the rural area (Bussotti et al., 1994).

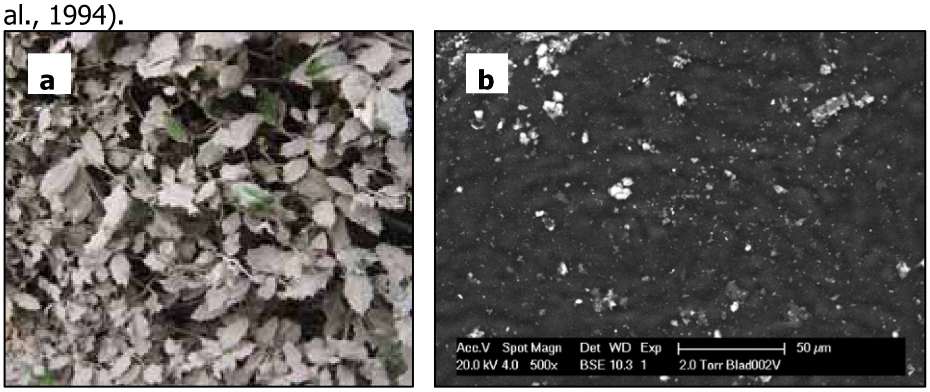


Figure 3.10a Dust on European Holly (Ilex aquifolium) leaves near an unpaved road. Figure 3.10b Micrograph (ESEM) of fine dust on common ivy (Hedera helix) leaf (M. Ottelé and A. Thijssen).

Also Thönnessen (2000) found heavy metal concentrations and fine particles on leaves of a green façade (*Parthenocissus tricuspidata*) in the inner city of Düsseldorf (daily traffic level 12.500 vehicles). Sternberg et al. (2010) found the same results by comparing ivy leaves from different sites (by counting particles on ivy leaves), the leaves from the sites exposed to a high daily traffic level, had collected a significant number of particles compared to the sites that are less exposed. Besides particle binding plants are also known to absorb gaseous pollutants through the stomata (CO_2 and NO_x). Via photosynthesis CO_2 is sequestered in the leaves (Minke et al., 1982). The negative health effects of particulate matter pollution for human's stands for decreasing lung functions, increased respiratory problems, and other health care visits for respiratory and cardiovascular diseases (Pope et al., 2009). Besides these effects also durability problems are involved and include accelerated corrosion of metals, as well as damage to paints, sculptures and soil-exposed surfaces on man-made structures (FFD, 2007). The improved air quality by green façades has direct benefits for people who suffer a long disease. A decrease of smog formation will occur, and also durability or corrosion problems are reduced of urban infrastructure that is susceptible to damage from air pollution (United Nations, 2007). Studies have shown that one mature beech tree (80-100 years old) with a combined leaf surface area of 1600 m^2 creates 1.71 kg of O_2 and 1.6 kg of glucose every hour (using 2.4 kg of CO_2, 96 kg of H_2O, and 25.5 kJ heat energy). This level of production is equal to the oxygen intake of 10 humans every hour (Minke et al., 1982). Another study carried out by the University of Dresden (2009) with regard to the organic balance of a greened façade with 1000 m^2 *Hedera helix* pointed out that in one year: 1019 kg of water and 2351 kg of CO_2 is consumed and bound respectively. In this reaction 5854 kg of organic mass (water content 4409 kg and dry mass 1415 kg) and 1712 kg of O_2 is produced.
With the assumption of an leaf area index (ratio between leaf surface in m^2 and covered wall surface in m^2) for *Hedera helix* of 2.6 up to 7.7 m^2 leaf/m^2 wall (Bartfelder and Kohler, 1987). The following leaf surface area can be calculated for the façade:

> Average value of the leaf area index of *Hedera Helix* ≈ 5.2 m^2 leaf/m^2 wall taking a greened wall surface of 1000 m^2 this results to:
> 5.2 x 1000 = 5200 m^2 of leaf surface.

Comparing this with the investigated mature beech tree of Minke (1982) with a leaf surface of 1600 m^2, a greened façade with *Hedera Helix* is more efficient to adsorb CO_2 and to produce O_2.

Field measurements carried out by Rath and Kießl (1989) on the effect of green façades on the SO_2 concentration shows that the concentration of SO_2 (figure 3.11a) was clearly lower between the foliage than in front of a non-greened façade. Fine dust concentrations were not measured or monitored during the research carried out by Rath and Kießl (1989).

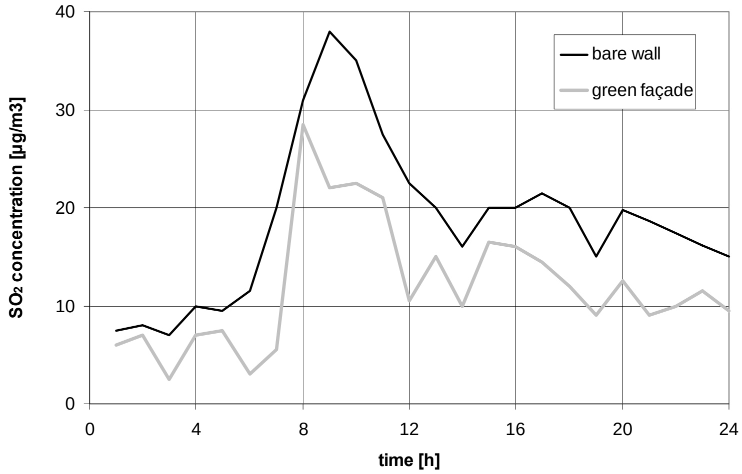


Figure 3.11a SO_2 concentration measured inside the foliage of an with ivy greened façade in Stuttgart-Vaihingen. From the graph it can be clearly seen that the green façade influences the SO_2 concentration in the air, according to Rath and Kießl (1989).

Field measurements conducted by a national research programme in the Netherlands (IPL) to investigate the effect of a vegetation corridor on the reduction of PM_{10} levels near a highway (A50), shows a minor contribution of the vegetation corridor on the concentration levels measured of the ambient air (figure 3.11b). They estimated the effect of vegetation smaller than 10-31% on the traffic contribution of particulate matter, due to the high uncertainty of the used measuring equipment.

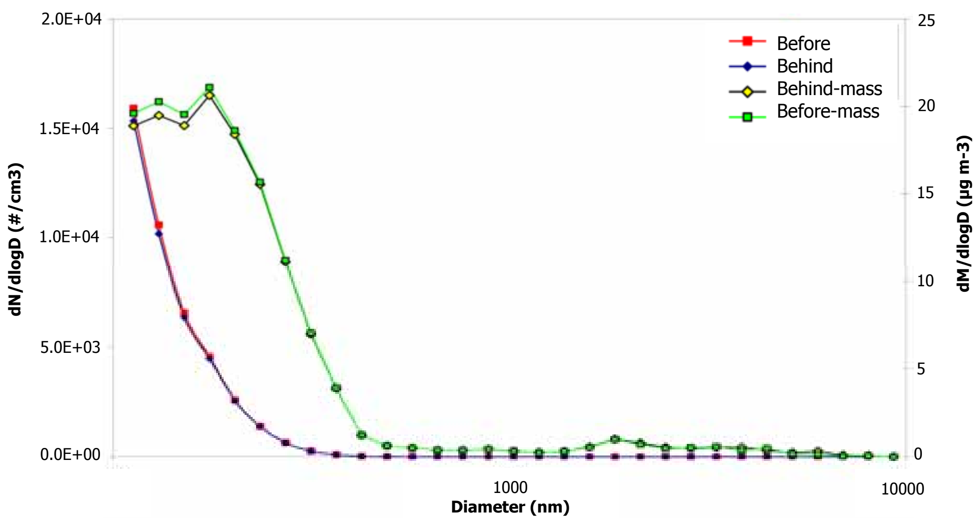


Figure 3.11b Particle size distribution (log-scale) measured before and behind a vegetation corridor next to a highway (A50). The number of particles suspended in the air given on the left axis, whereas particle mass is given on the right axis, according to Vermeulen et al., 2009 and IPL, 2009.

3.4.2 Ecological aspects

Vertical gardens can be designed as acceptable alternative ecological habitats. Particular species such as *Hedera helix* and for example climbing roses (*Rosa*) produce colourful berries enjoyed by birds in winter time. When we look at the façades or outside walls of buildings, green systems will show ecosystem characteristics, they will function as a habitat, show structure, material and energy flows. But it will also provide ecological services like breeding and resting habitat for birds which may be enjoyed by humans. Not only for micro-organisms an undisturbed habitat is created but also for smaller animals (bees, bats, birds, etc.) it is suitable.

Figure 3.12 (Green) façades and house sparrows a symbiosis between the built environment and nature (weidevogelbescherming-weerselo).

Climbing plants are particularly favoured by birds and bats. Façades studied in Berlin show that mainly house sparrows, blackbirds and greenfinches are found between the climbers (Köhler, 1993). Green façades functions hereby as a food source (insects) and as a nesting or breeding opportunity.

The current form of urbanization for example is negative for house sparrows; since the current building design leads to a lack of nesting occasions in buildings (Vogelbescherming Nederland, 2010). A wide range of artificial structures have been used throughout the world to provide nest sites for a great range of birds and bats (Johnston et al., 2004). Many types of these artificial nest boxes can be attached or incorporated to the outside of new or existing (green) buildings. Integrating nature on new buildings allows for the possibility to choose for built-in nest boxes which can be incorporated into the ecological design. Last but not least watching these animals can be a source of considerable pleasure to city dwellers as well. Incorporating nest boxes into green façade concepts (linking of functions) will increase the impact of these measures relatively to when applied separately.

Not only birds are attracted by green façades and roofs. A biodiversity study of 17 green roofs in Basel indentified 245 beetle and 78 spider species in the first three years after installation of the roof. Eleven percent of the beetles and 18% of the spiders were listed as rare or endangered (Brenneisen, 2003). Also Köhler (1988) concluded from his research that climbing plants (for example *Hedera helix* and *Parthenocissus*) form an important habitat for insects. Mainly beetles, flies and spiders are found inside a green façade (Bartfelder and Köhler, 1987).

Figure 3.13 Green façades forms an habitat for different small animals and insects (Plattelandsvereniging Hei, Heg & Hoogeind).

3.4.3 Protection against driving rain and sun radiation

Well developed green façades (closed foliage) forms an effective protection against driving rain, because it prevents that the rain will reach the surface of the façade. Investigations done by Rath and Kießl (1989) on greened and non greened façades pointed out that with well developed foliage no rain will reach the wall surface. Rath and Kießl (1989) also found that 50% of the solar energy was adsorbed and 30% was reflected by the foliage. Beside the adsorption and reflection they measured that approximately 20% of the radiation passes the foliage and reach the surface of the façade. This means that a plant covered façade can shield off roughly 80% of the solar radiation while a bare façade receives 100% direct exposure. This filtering of the radiation by the foliage can lead to protection or a reduction in maintenance of cladding, painting, coatings or other building materials that are sensitive to UV deterioration. As a consequence these effects also thermal stresses inside building materials will be reduced.

3.4.4 Temperature regulation and insulating properties

Living walls and green façades create their own specific microclimate, quite different from surrounding conditions. Due to this specific micro climate both around the building and at grade are affected. Depending on height, orientation and the location of surrounding buildings, the façade is subjected

to extreme temperature fluctuations (hot during the day and cool at night), with constant exposure to sunlight and wind. The climate at the façade is comparable with arid or alpine climate and only suitable to specific types of plants.

Figure 3.14 Boston ivy (Parthenocissus) rooted in the soil and applied directly against the façade in Delft summer 2009.

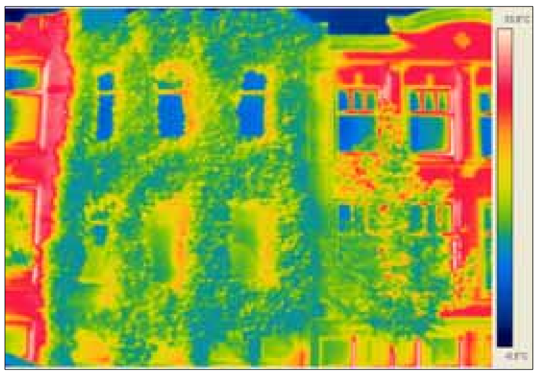


Figure 3.15 Photograph taken of the same façade with an infrared camera (FLIR) with ambient air temperature 21 °C.

Hard surfaces of concrete and glass encourage runoff of rainwater into the sewage system. Plants buffer water on their leaf surfaces longer than building materials and the processes of transpiration and evaporation, can add more water into the air. The result of this is a more pleasant climate in the urban area. Between façade and the dense vertical green layer (for both rooted in the subsoil as rooted in artificial soil based systems) a stagnant air layer exist. Stagnant air has an insulating effect; green façades can therefore serve as an "extra insulation" of the building façade (Minke et al., 1982, Krusche et al., 1982). Also direct sunlight on the façade is blocked by the vegetation. This blocking of the sunlight ensures that the temperature will be less high inside a house. In winter, the system works the other way round and heat radiation of the exterior walls is isolated by evergreen vegetation. In addition it is claimed in literature that dense foliage will reduce the wind speed along the façade and thus also helps to prevent that the walls will cool. As a consequence every decrease in the internal air temperature of 0.5 °C will reduce the electricity use for air conditioning up to 8% (Dunnet and Kingsbury, 2004). Green façades and roofs will cool local air temperatures in two different ways. First of all, walls behind greened surfaces absorb less heat energy from the sun (traditional façade and roof surfaces will heat up the air around them). This effect is clearly visible in figure 3.14 and 3.15 where uncovered parts of the façade are heated up (colour red) are the parts covered with leaves considerable lower (colour blue and green). Secondly, green façades and roofs will cool the heated air through evaporation of water (Wong et al., 2009)

(for evaporation of 1 kg water, 2.5 MJ of energy is necessary); this process is also known as evapo-transpiration.
Most of the sun's radiation that is adsorbed by concrete, bituminous materials or masonry is re-radiated as sensible heat. Asphalt, concrete and masonry will reflect 15 to 50% of the received radiation they receive (Laurie, 1977), greening paved surfaces with vegetation to intercept the radiation before it can hit hard surfaces can reduce the warming up of hard surfaces, especially in dense urban areas. In an urban heat island effect situation, even night air temperatures are warmer because of built surfaces adsorb heat and radiate it back during the evening hours (Getter et al., 2006).
From 100% of sunlight energy that falls on a leaf, 5-30% is reflected, 5-20% is used for photosynthesis, 10-50% is transformed into heat, 20-40% is used for evapotranspiration and 5-30% is passed through the leaf (Krusche et al., 1982). In the urban area, the impact of evapotranspiration and shading of plants can significantly reduce the amount of heat that would be re-radiated by façades and other hard surfaces. Besides that, the green plant layer will also reduce the amount of UV light that will fall on building materials. Since UV light deteriorates material and mechanical properties of coatings, paints, plastics, etc. plants will also have an effect on durability aspects. This is a beneficial side effect which will have a cost effective effect on maintenance costs of buildings. The denser and thicker the plant layer on the green façade, the more beneficial these effects are.
The role of insulation materials and stagnant air layers is to slow down the rate of heat transfer between the inside and outside of a building, which is a function of the difference between the inside and outside temperatures. An insulation material mitigates the impact of the temperature difference between inside and outside. In winter conditions the insulation material slows down the rate of heat transfer to the outside. In summer conditions the opposite is the case; it slows down the rate of heat transfer from the outside to the inside. The greening of vertical surfaces has a beneficial effect on the insulating properties of buildings through exterior temperature regulation (Krusche et al., 1982). The insulation value of vertical greened surfaces can be increased basically by different mechanisms (Peck et al., 1999; Rath and Kießl, 1989; Pérez et al., 2011):

- By covering the building with vegetation, solar radiation is prevented reaching the building skin (shading effect of leaves), and in the winter, the internal heat is prevented from escaping.
- Since wind decreases the energy efficiency of a building by 50%, a plant layer will act as a buffer that keeps wind from moving along a building surface.
- The thermal resistance of a construction can be reduced from 23 W/m^2K to 12 W/m^2K.
- The thermal insulation provided by vegetation and substrates used (mostly related to living wall concepts).

Table 3.3 Assumption done by Minke (1982) on the improvement of a green façade on the thermal insulation values.

Construction layers	1/λ	(m^2K/W)	m^2K/W)
1/α inside	0.13	0.13	0.13
2 cm gypsum	0.02	0.02	0.02
36 cm masonry (1600 kg/m^3)	0.56	0.56	0.56
2 cm gypsum	0.02	0.02	0.02
1/α	0.04	-	-
1/α outside, changing	-	0.13	-
4 cm air cavity (α=0.1)	-	-	0.40
Σ1/λ	0.77	0.86	1.13
R (m^2K/W)	1.30	1.16	0.88
Energy saving in %	0	11	32

Krusche et al. (1982) claims that the air cavity between leaves and façade decrease the heat transfer from façade to the outdoor air. A green façade with a leaf cover of a size of 5 cm yields a k-value of 2.9 W/m^2K which is comparable with double glazing (Krusche et al., 1982). The k-value (in recent standards denoted as the U-value), or heat transfer coefficient, is the measured value of the heat flow which is transferred through an area of 1 m² at a temperature difference of 1 K. The U-value can be found by the reciprocal of the thermal resistance (R-value) of a construction.

Table 3.4 Improvement of the insulating value of a well greened façade (5 cm stagnant air layer between leaves and façade) depending on the U-value of the façade according to Krusche et al., 1982.

Façade without green	Greened façade	Improvement
U-value	U-value	%
1.5	1.0	33
1.0	0.75	25
0.6	0.5	16
0.3	0.27	10

This “green” strategy of increasing exterior insulation properties of vertical surfaces stimulates upgrading or retrofitting of existing (under-insulated) façades without the added cost of interior or traditional exterior insulation (see table 3.4).

The behaviour of greened façades not only influences the interior climate but also the outer climate is affected. Bartfelder and Köhler (1987) measured differences in temperature as a function of different distances in front of a façade (table 3.5). Also Rath and Kießl (1989) measured differences in the temperature gradient across an with green covered wall up to 10 °C. The corresponding factor in both researches is that at 1 m in front of the vegetation layer no temperature differences were measured between the greened and non-greened façades. However the temperature difference at the wall surface between a greened and non greened façade is approximately ca. 6 °C.

Table 3.5 Measurement of Bartfelder and Köhler in summer 1982 of a bare façade and a façade greened with Hedera helix according to Bartfelder and Köhler (1987).

Green façade research Berlin summer 1982								
Period		Uncovered			Covered with green			
	Parameter:	T_1	T_{01}	T_0	T_{1p}	T_{01p}	T_{0p}	
All days (n=133)	Max.	20.8	22.2	31.0	21.4	22.2	25.2	
	Min.	12.4	13.1	16.7	12.6	14.1	16.3	
	Amplitude	8.4	9.1	14.3	8.8	8.1	8.9	
Sunny days (n=64)	Max.	24.1	25.6	36.0	25.1	24.8	28.6	
	Min.	13.0	13.8	17.2	14.5	13.1	17.2	
	Amplitude	11.1	12.2	18.8	10.6	11.7	11.4	
Minimum temperature (n=133)	Max.	6.2	6.1	11.2	7.9	6.8	9.9	
	Min.	1.0	1.2	7.0	3.0	0.9	3.8	
	Amplitude	5.2	4.9	4.2	4.9	5.9	5.2	
Maximum temperature (n=133)	Max.	35.2	38.7	44.8	34.6	36.0	40.7	
	Min.	22.0	22.9	24.8	22.1	21.2	27.6	
	Amplitude	13.2	15.8	20.0	12.5	14.8	13.1	
T_1	temperature 1 m before façade							
T_{01}	temperature 10 cm before façade							
T_0	temperature of façade							

This means that a greened façade adsorbed less heat then a non greened façade and reveal itself in less heat radiation in the evening and night. In this way a greened façade contributes in mitigation of the urban heat island effect. In figure 3.16 one can see the influence of different surfaces on the temperature development over twenty four hours. Water surfaces (sea, lake) shows a lower peak and delayed temperature development due to evaporation of water, also woodland show this characteristic (plants, vegetation contains also water). Hard surfaces such as concrete and asphalt show a high thermal capacity and surface temperature.

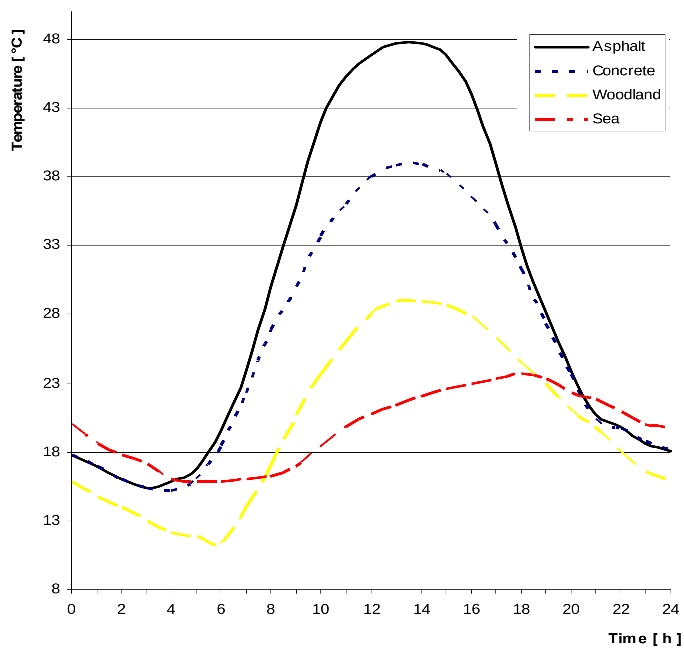


Figure 3.16 Temperature development of different surfaces on a summer day adopted/adjusted to Krusche et al., 1982.

3.4.5 Sound adsorption and noise reduction

Plants can absorb, reflect and diffract noise, this effect could lead to a more comfortable and pleasant environment in urban areas. The efficiency appears to be dependent from the plant type, planting density, location and sound frequency (Rutgers, 2011). For indoor application the acoustical performance of a number of typical indoor plant species is defined by Costa (1995).

Table 3.6 Absorption coefficients for a number of single indoor plant species according to Costa (1995).

Typical absorption coefficients						
Plant species	Sound Frequency (Hz)					
	125	250	500	1000	2000	4000
Ficus benjamina	0.06	0.06	0.10	0.19	0.22	0.57
Howea forsteriana	0.21	0.11	0.09	0.22	0.11	0.08
Dracaena fragrans	0.13	0.14	0.12	0.12	0.16	0.11
Spathiphyllum wallisii	0.09	0.07	0.08	0.13	0.22	0.44
Dracaena marginata	0.13	0.03	0.16	0.08	0.14	0.47
Schefflera arboricola	-	0.13	0.06	0.22	0.23	0.47
Philodendron candens	-	0.23	0.22	0.29	0.34	0.72
to compare						
Bark mulch	0.05	0.16	0.26	0.46	0.73	0.88
Thick pile carpet	0.15	0.25	0.50	0.60	0.70	0.70
Plasterboard	0.30	0.15	0.10	0.05	0.04	0.05
Fresh snow, 100 mm	0.45	0.75	0.90	0.95	0.95	0.95

The above mentioned measurements are however for single plants, valid for indoor and thus not applicable for green façades outdoors. From the measurements done by Costa, it can be derived that the effect of single plants on sound absorption is low compared with other materials. However greened façades either greened directly, indirectly or with a modular living wall concept can be seen as a multilayered system. Due to the materials used, it is likely that the effect on sound adsorption will be larger than for single plant sound measurements. Research conducted at the National University of Singapore by Wong et al. (2010), was focussed on the effect of sound adsorption by different vertical greening systems. They measured the inertial loss and sound absorption coefficient of nine different vertical green cladding systems placed outdoor (table 3.7). The inertial loss was measured by microphones 1.5 meters above the ground 1 m in front of the façade and 2 m behind the green wall systems (figure 3.17). A sound calibrator was placed 2 m in front of the greened façades to test the system on a frequency range of 63-10 kHz.

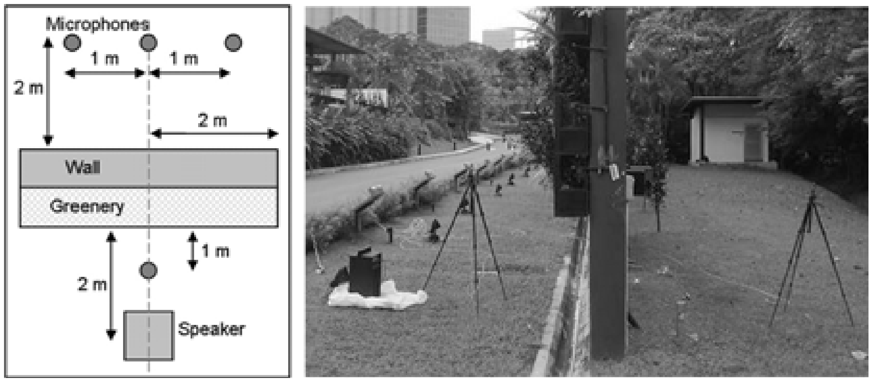


Figure 3.17 Experimental set-up as used in Hortpark (Singapore) Wong et al., 2010.

Table 3.7 Description of eight vertical greenery systems as tested in HortPark (Wong et al., 2010).

Vertical greenery system			Average thickness (m)		
			Substrate	Plants	Total
Green façade	Vertical interface	1	0.250	0.100	0.350
	Mesh system	2	0.080	0.010	0.090
		3	0.230	0.120	0.350
		4	0.080	0.120	0.200
Living wall	Angled interface	5	0.070	0.110	0.180
	Horizontal interface	6	0.065	0.055	0.120
		7	0.060	0.120	0.180
		8	0.280	0.200	0.480

Additional Wong et al. (2010) measured a vertical greenery system in a reverberation chamber. As plant species *Nephrolepis Exaltata* (Boston fern) placed in pots on wooden racks was used for this experiment. In total 140 pots of plants were defined as covering the façade by 100% with foliage, subsequently 100 and 60 plants were defined as 71% and 43% covering. The materials used for this experiment were the same as for the field measurements. The used reverberation chamber was 136 m^3.

From the insertion loss experiment it was found that there was a strong attenuation at low to middle frequencies due to the effect of the substrate used while a smaller attenuation was observed at high frequency due to the scattering of the greenery. The eight tested systems in Hortpark are more effective at reducing lower frequency noise source. However from table 3.8 it can be derived that the systems 1, 2, 5, 6, 7 have a reduction of around 5-10 dB for the low to middle frequency range, which is perceptible or even clearly noticeable for human perception in the change of sound intensity (Wong et al., 2010).
The sound absorption coefficient (table 3.9) of the tested vertical greenery system (three different percentages of foliage cover) in the reverberation

chamber has one of the highest values compared with other buildings materials and furnishings. The substrate in the systems does most of the absorption. The greened façade appears to have a positive effect on the reverberation time, especially in the frequency range between 200 Hz - 1 KHz (Wong et al., 2010). The substrate (soil) mixture performs well in low frequencies by absorbing the acoustics energy; plants perform better at higher frequencies (Wong et al., 2010). The relationship between the greenery coverage and the sound absorption coefficient is observed that with greater greenery coverage, there is an increase in the sound absorption coefficient.

Table 3.8 Summary of insertion loss according to Wong et al., 2010.

Vertical greenery system	Insertion loss (dB)			
	Zone B: 125-1250 Hz		Zone D: 4-10 kHz	
	Lowest	Highest	Lowest	Highest
1	2.5	5.6	0.6	3.1
2	1.1	9.9	2.2	3.8
3	4.5	2.2	4.0	3.2
4	1.5	4.0	2.5	2.0
5	3.3	7.0	0.3	2.8
6	2.4	5.4	1.6	3.2
7	0.3	8.4	0.0	3.9
8	0.6	3.1	2.6	8.8

Table 3.9 Summary of sound absorption coefficient according to Wong et al., 2010.

Frequency (Hz)	Sound absorption coefficient (greenery coverage)		
	43%	71%	100%
100	0.06	0.04	0.04
125	0.12	0.10	0.09
160	0.10	0.11	0.14
200	0.17	0.18	0.18
250	0.25	0.28	0.23
315	0.31	0.30	0.29
400	0.32	0.30	0.32
500	0.51	0.47	0.49
630	0.57	0.55	0.47
800	0.50	0.44	0.41
1000	0.61	0.54	0.48
1250	0.54	0.57	0.49
1600	0.65	0.57	0.51
2000	0.66	0.56	0.49
2500	0.64	0.57	0.50
3150	0.62	0.56	0.49
4000	0.57	0.51	0.47
5000	0.58	0.54	0.48

3.4.6 Social impact

People seem to feel better in a green environment which is mainly related to psychological influence. This phenomenon is called biophilia and suggests that people feel better next to all that is alive and vital (Rutgers, 2011). Rutgers (2011) mentioned in his study that it is a feeling of a bond between humans and other live forms that comes from "the connections that human beings subconsciously seek with the rest of life" as stated by Wilson (1984). Studies conducted in the past show clearly the effects that plants have on human health, it is found for example that visiting a botanical garden lowers blood pressure and reduces heart rate (Owen, 1994). Ulrich (1991) shows that the presence of vegetation will speed up recovery from stress and in earlier research Ulrich (1984) pointed out that patients who have access to windows, looking on a natural scene, had shorter postoperative hospital stays. Fjeld (1998) shows the score sum of symptoms of discomfort was 23% lower during the period when subjects had plants in their offices compared to the control period.

3.4.7 Costs

Buildings consume 36% of total energy use and 65% of the total electricity consumption. Kula (2005) suggests that a wide scale green roof implementation could significantly impact energy savings. Mostly a building encompasses a larger façade surface than a roof surface, it seems therefore plausible that greening façades would lead to a larger significantly impact on the energy savings compared with a green roof. According to Dunnet and Kingsbury (2004) every decrease of the internal building temperature with 0.5 °C may reduce the electricity use with 8% for air conditioning in summer periods. Akabari et al. (2001) concluded that since 1940 the temperatures in urban areas have been increased by about 0.5-3 °C. For each 1 °C increase in temperature in cities, the electricity demand is typically increased by 2-4%. Akabari et al. (2001) estimated that 5-10% of the current electricity demand of cities is used to cool buildings just to compensate the 0.5-3 °C increased temperature. Mitigation of the urban heat island effect with trees, green roofs and green façades can reduce the U.S. national energy consumption for air conditioning with 20% and save more than $10B in energy use (Akabari et al., 2001).

However there are more processes and costs involved due to lower outdoor temperatures. Lower electricity demand involves also less energy production at the power plant. If the power plant is coal fired this means also less emissions, and thus a decrease of the air pollution (figure 3.18 adapted after Akabari et al., 2001). If there is less air pollution this affects for example also human health with respect to lung or cardiovascular diseases caused by fine particles or smog formation. Costs are not only related to energy savings and a reduction of air pollution levels, but also for example increase of the real estate values in dense areas. Due to the use of more green in the neighbourhood houses can even gain up to six percent extra values due to a good tree cover in the surroundings (Morales, 1980).

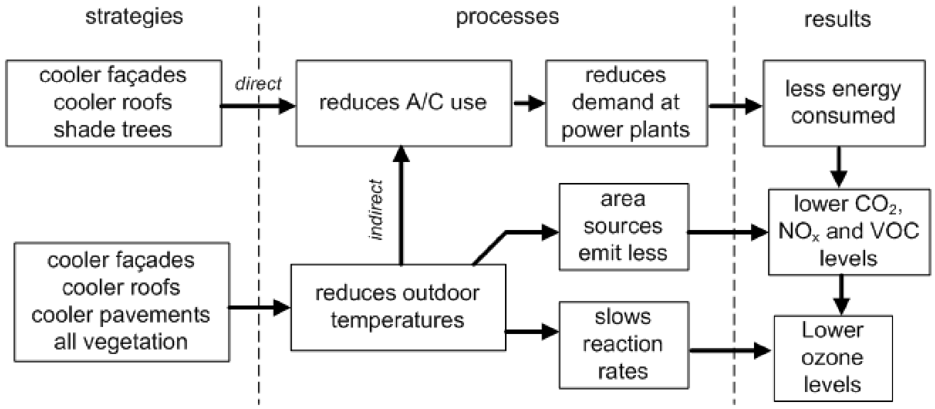


Figure 3.18 Methodology to analyze the impact of cool façades, roofs and pavements on energy use (adapted with green façades after Akbari et al., 2001).

Green façades or vertical green are also an expensive cladding technique at the moment. Research done by Middelie (2009) and Perini et al. (2010) about the initial costs to construct a green façade based on living wall systems, pointed out that the price range lay between 350 till 1200 euro per square meter façade. This is however only an indication because at large purchase the prices will be consequently differently. The living wall systems increase the variety of plants that can be used beyond the use of climbing plants and offers much more creative (aesthetical) potential. It is also possible to assume that, from a functional point of view, most of the living walls systems (LWS), compared to green, demand a more complex design, which must consider a major number of variables (several layers are involved, supporting materials, control of water and nutrients, etc.), on top of which they are often very expensive, energy-vorous and difficult to maintain. Considering the large amount of systems available on the market in all Europe, it is possible to give an idea of the costs needed for installing the systems described below.

Range of costs for vertical greening systems per m^2 (in Euros):

a. Direct greening system (grown climbing plants): 30-45 €/m^2
b. Indirect greening system (grown climbing plants + supporting material): 40-75 €/m^2
c. Indirect greening system with planter boxes (LWS):
    - Zinc-coated steel (galvanized) 600-800 €/m^2
    - Coated steel 400-500 €/m^2
    - HDPE 100-150 €/m^2
d. Living wall system based on planter boxes HDPE: 400-600 €/m^2
e. Living wall system based on foam substrate: 750-1200 €/m^2
f. Living wall system based on felt layers: 350-750 €/m^2

Within the range given, the costs depend on the façade surface (equipment) and height, location, connections, etc. It is clear that the living wall systems are much more expensive than the direct and indirect greening systems, this is due to the maintenance needed (nutrients and watering system), the materials involved, the design complexity. It also has to be taken into account the durability of the systems, for example a panel of a LWS based on felt layers has an average life expectancy of ten years, but the LWS based on planter boxes (HDPE) is more durable (more than fifty years according to Riedmiller and Schneider, 1992). Beside this a thorough design (details of window ledges, doors, etc.) is necessary to avoid damages, as corrosion or rot, caused by water and nutrients leakage which involves also extra costs.

3.5 Risks of vertical green

3.5.1 Moisture problems

In contrast with what is frequently thought, climbing plants are in general beneficial to the façades. Rainwater is removed by the foliage to the subsoil before that it can come in contact with the façade. Also Rath and Kießl (1989) concluded that well greened façades work beneficial as barrier against driving rain.
The three investigated façades (one with Virginia creeper (*Parthenocissus)*, two with ivy (*Hedera helix)*) shows that the driving rain loads were reduced to zero compared with a non greened façade.

Nevertheless it is frequently discussed that there are potential moisture problems at older green façades (Maes, 1992). This is partly true, if the façade for whatever reason has become wet, it will dry up more slowly if there are climbers (directly) against the façade. This is because of the reduced air flow and solar radiation penetration between the foliage and façade which slows down the evaporation rate. However covering the façade with climbing vegetation promotes under no circumstances the moisture of the façade. Removing the climbing plants however can have an unexpected effect on the moisture content of the façade (Maes, 1992).

Humidity measurements carried out by Bartfelder and Köhler (1987) on a summer day show for a with ivy *(Hedera helix)* greened façade, that it was drier on all the measuring points compared with the bare façade (figure 3.19). Rath and Kießl (1989) found according to drilled masonry cores, from bare and greened façades, that the moisture content in the cores was primary coming from driving rain and validate therefore the findings done by Bartfelder and Köhler (1987). Evergreen climbing species are useful year-round; deciduous species will automatically lead to wetter façades in winter periods. The living wall concepts form however an exception due to the prefab panels used. The modules used for these systems can be seen as an excellent rain and moisture protection due to the materials used.

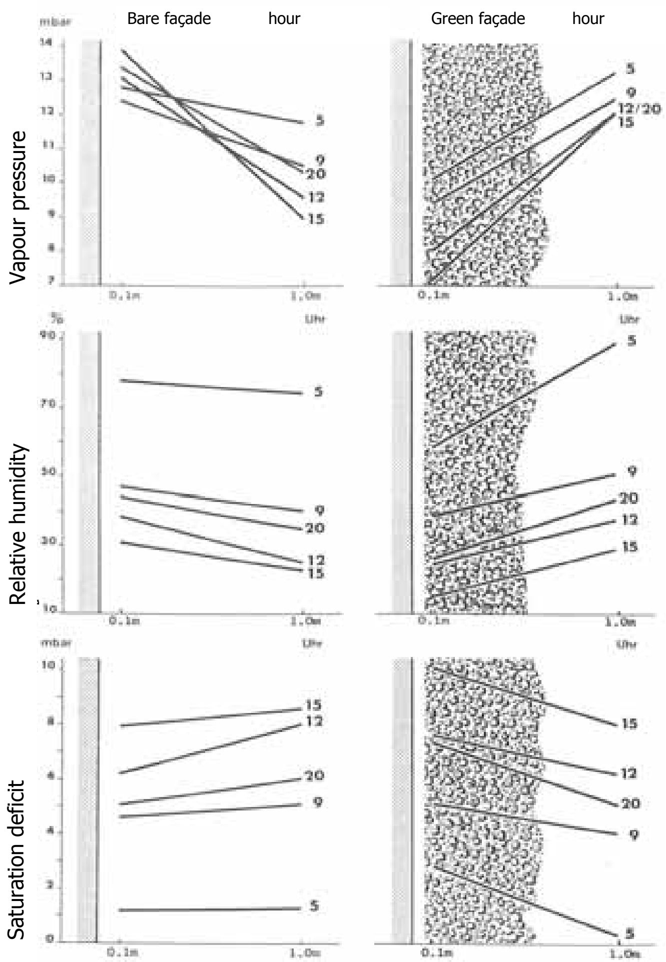


Figure 3.19 Moisture measurements done on a summer day at a west orientated bare and greened (Hedera helix) façade in Berlin (26 July, 1983) according to Bartfelder and Köhler (1987).

3.5.2 Damage and deterioration

It is a misconception that green façades will damage the wall (ripping out mortar and prising apart joints with their roots) they are covering; as long as the original cladding is in good repair roots will not threaten the integrity of the wall. However damaging and deterioration related to plant covered structures suggests that these problems have been greatly exaggerated. Where deterioration has already set in, plants can indeed accelerate the process of deterioration (Johnston et al., 2004). Plant covered surfaces protect the exterior (for example wood or masonry) from ultra violet radiation (UV), driving rain and temperature differentials. Despite centuries of plant growth ancient walls still stand, with indeed the suggesting that any damage to the walls by plants is a very slow process (Johnston et al., 2004). A façade can heat up easily to 60 ºC and then cool to minus 10 ºC. With a layer of plants, temperatures will only fluctuate between 30 ºC and 5 ºC (Minke, 1982). A layer of vegetation which protects a building from UV radiation may also reduce the thermal tensions within the structure due to temperature fluctuations (Doernach, R., 1979). The foliage protects the façade against warming up by the sun in summer and in cooling off in winter as mentioned above. However, we have to take into account a number of aspects related to possible deterioration and or damaging effects by the use of climbing plants for vertical surfaces (of buildings). Damage can be caused mainly by self clinging plants (*Hedera helix, Parthenocissus*) if cracks or holes in a wall are already present (Maes, 1992). When the mortar joints are very soft or porous the application of self clinging plants is discouraged. Also Mishra et al. (1995) stated that biophysical decay is mainly related to growth and radial thickening of the roots of the plants which results in an increase in the pressure (the mean pressure of roots is of the order of 15 atmospheres) on the surrounding areas of the masonry. Consequently, woody species are expected to cause much more damage as a result of secondary growth in their roots and stems resulting in appreciable dimensional changes compared to herbaceous plants (Mishra et al., 1995). One of the properties of self clinging plants is that the roots are negative phototropic (Köhler, 1993); they grow away from the light and develop their selves in a dark environment (for example cracks). A study in Berlin (Köhler, 1993) on the condition of the render in combination with self clinging plants shows the protective capacity of the plant layer as well. Only 1% of the investigated façades has severe damage, 16% shows some damage and 83% were undamaged. The created damage is most likely caused by self clinging plants when they are pulled off from the façade. This will happen when the plants are dead and unsightly or as part of trimming operations (Dunnet and Kingsbury, 2004). Mishra et al. (1995) reports beside a physical mechanism also a chemical mechanism of deterioration. This mechanism is affected by the release of exudates which react chemically with the substrate or may result in the erosion of the surface on account of uptake of calcium or other ions present in the substrate.

Figure 3.20 An old façade (brick wall with porous lime stone mortar joints) in the inner city of Berlin partially covered with Boston ivy (Parthenocissus). Although not advisable to use a direct

greening system; the foliage preserves against further deterioration by weather influences (driving rain).

They refer to root marks on marble and limestone due to the etching effect of the slightly acidic sap of the root cells, however it is only visible after removing of the green layer (greened directly). Despite possible damage on building surfaces as mentioned before Maes (1992) concluded that self clinging plants can help preserve old buildings (monuments) from decay. According to Mishra et al. (1995), the presence of plant growths over the surface may result in persistent dampness in the walls (and is the opposite as found by Bartfelder and Köhler (1987) and by Rath and Kießl (1989), chapter 3.2.1) or disturb the footings, plinths, eaves courses, etc. and create in time obstructions for regular maintenance of structures. Other problems can occur when climbing plants will be used in order to cover façades. One can think about blockage of roof gutters or leakage of roof tiles through branches. When drain pipes are used as guide, notice that damage can occur via thickness growth of the stems. If climbing plants are planted in the subsoil against the façade damage to (sewer) pipes is limited to older and already failing systems (Köhler, 1993). Damage to the foundation is not unknown but extremely rare according to Köhler (1993). A new form of damages is emerging for vertical greened façades; those problems are related to the living wall concepts and exist mainly in moisture and in the die off of vegetation. Although the living wall concepts are not widely constructed yet, the first designed façades show common problems as for example can be seen in figures 3.21 and 3.22, taken in the Netherlands (Amsterdam) and Spain (Madrid). Dripping around window ledges causing stripes and possible rot of the wind casing itself, but also unattractive bare areas are visible were the chosen plant species can not survive. A good design regarding connections, watering system and suitable plant species is required to avoid these (mistakes) small problems.

Figure 3.21 Mercator sportplaza in Amsterdam (The Netherlands), left photograph; detail of an opening in the façade and accompanying water leakage problems. Right photograph shows open areas in the vegetation due to dying of several plant species (several reasons can be mentioned to

this failure such as wrong type of plant species used or a problem in the watering system (too dry), Photos Barbera Peters.

Figure 3.22 Left photograph Caixa forum in Madrid; bare surface of the vertical placed panel, water leakage and degradation of the substrate is visible (felt pockets). Right photograph belongs to the same façade were they solve the leakage with a gutter filled with gravel for drainage and avoiding splashing of water droplets (Photos Barbera Peters).

Beside degradation processes, which affect the construction (directly) related to the presence of vegetation, it is also possible to speak about (indirectly) bio deterioration processes. The absorption of fine and ultra fine particles due to the foliage cover may reduce decay processes on stone walls. This suggests that climbing plants can retard bio deterioration of building façades and thus serve a conservation role on historic buildings (Sternberg et al., 2010). Findings by Sternberg et al. (2010) highlight the potential for climbing plants to act as a protective layer that mitigates particle deposition on structures in metropolitan areas.

3.5.3 Maintenance

Vertical greened surfaces need organized management and maintenance. Required maintenance of green façades (direct and indirect) is limited to occasional sorting of climbers entering guttering or tendrils twining around window fixtures. The omission of maintenance can lead to a negative impression. Where there is a possibility for shoots to penetrate between or in materials, for example under tiles, cladding or roofs, this growth will need to be cut back to ensure that the façade does not interfere with the fabric of the building. With careful planning and considered design of the support system most green façades need very little maintenance (Stainless steel solutions, 2010). Façades covered via a living wall system (LWS) with sophisticated planting combinations may need a certain amount of maintenance. Maintenance is mainly related to the vegetation and not to the construction itself. However, the irrigation system that is needed for these systems must be deflated in winter to prevent frost damage, and additional required nutrients (plant growth) must be replenished occasionally. Maintenance of the vegetation consists mainly of pruning (figure 3.23a) twice a year with a (mobile) crane and possibly replanting (figure 3.23b) in places where the vegetation is deteriorated (Hendriks, 2009). This problem is mainly related to the living wall systems, advisable is to check annually the façade in spring. In some cases it is also possible to replace prefab panels with new pre-vegetated panels to reach instantly a green(er) result.

Figure 3.23a Maintenance an annual deficiency of green façades, above the dashed line has to be pruned each year to avoid that the shoots will grow over the roof, Photo Ashraf Mir.

Figure 3.23b Maintenance in the case of a living wall system (based on felt layers) includes: checking the integrity of the substrate(s), functioning of the watering system and replanting of bare parts of the façade.

4 From theory to an experimental approach; quantifying the benefits

4.1 Introduction

It is well known in literature that natural vegetation in urban areas affects the air quality and the overall experience of health and well-being of humans living in urban areas (Currie and Bass, 2008). Vegetation is capable to filter different types of air pollution as discussed before. Fine particles or fine dust is one of those pollutants that has an enormous impact on the build environment and quality of life of humans. The first step in determine the effect of vegetation on particle reduction is to investigate the relation between particles and plants and to quantify this relation. Quantifying the effects and contribution trough green façades in particular on air pollutants within the urban area however is a relatively new field to investigate. And beside this, what is the best way to classify these effects and which method will be used? The method used in this doctoral research is based on counting (fine) particles on leaf surfaces. The counting method can give answers on the amount of adhered particles on the leaf surface, but also on the effect of a treatment (for example rain) on the particle amount. Besides counting particles the use of an electron microscope enables also to classify particles according to their elemental origin.

4.2 Ecological Engineering, Greening of vertical walls and roofs of buildings in the urban area

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M. Ottelé, H.D. van Bohemen and A.L.A. Fraaij
Delft University of Technology, Faculty of Civil Engineering and Geosciences, Stevinweg 1, 2628 CN Delft, P.O. Box 5048, The Netherlands. Corresponding author: E-mail: M.Ottele@tudelft.nl, T +31 (0)15 2787439, F +31 (0)15 2786383

Abstract
Throughout history greening of outside walls and roofs of buildings has taken place. Reasons for doing so were the increase of insulation (keep cool in summer and keep heat inside in winter), improved aesthetics, improved indoor and outdoor climate, catching of NO_x and Particulate Matter (PM_x), as well as increasing ecological values by creating habitats for birds and insects.

The paper will show within the context of ecological engineering the impact of green roofs and the greening of outdoor walls and question the hesitation to implement green walls as outer layer of buildings. Special attention will be given to the relation between particulate matter and aerosol deposition and vegetation. An overview and comparison of different types of wall greening for housing as well as for industrial and other commercial buildings will be given. Some concrete examples will be elaborated to show possibilities of multi-functionality:

- Combining green walls with the green roof concept as part of the ecological infrastructure in built-up areas
- Combining indoor and outdoor plantings
- Combining greening of walls and green roofs with waste water treatment systems.

The paper will also show how to organize a program for large scale implementation of green building envelopes as integrated approach in order to make greening of walls feasible from the design concept till the maintenance phase.

Keywords: Ecological engineering, Ecosystem functions, Sustainability, Urban ecology, Particulate matter (PM_x), Green roofs, Green walls (façades).

Introduction

Ecological engineering, defined as 'the design and realization of sustainable ecosystems that integrate human society with its natural environment for the benefit of both' (Mitsch and Jørgensen, 1989, 2004) can play an important role in urban planning and construction of civil engineering objects, like buildings. Realization of green roofs and greening of vertical walls can be considered as examples of ecological engineering. The realization of vegetated roofs finds more and more frequent application in the building sector, although for large scale application there is in general still hesitation among policy makers and designers. This is a great pity as financial details show that applications of green roofs are not any more expensive than traditional flat roofs, beside the positive environmental values.

Greening of outside walls or façades of buildings is getting also more interest in recent years. Although the concept is not new (in the eighties of the 20th century different report and books have been published, like Liesecke (1985), the negative impacts have gained more interest than the positive values. But the positive effects are coming more and more to the forefront, to make a more balanced approach possible. This paper will show the success as well as the fail factors of greening of façades of buildings. It will compare the natural with the artificial situations and on the basis of a comparison existing greening wall system will be evaluated. It will also be shown how to improve the design as well as the planning and building phase.

Ecological engineering

Mankind is fully dependent on ecosystem functions, goods and services (oxygen provision, CO_2 absorption, provision of renewable raw materials, biogeochemical cycles, habitats for plants and animals, etc.). The impact of human activities on the environment is increasing due to the increase of welfare and increase of the world's population. People are more and more interested in reducing the negative effects on the environment, which can be seen in practice as well as in different disciplines in our society. Odum (1983) and Mitsch and Jørgensen (1989, 2004) introduced ecological engineering as a combination of various disciplines: ecology and technology. Ecological engineering is not limited to the restoration of nature: it is focused on the conservation, rehabilitation and restoration of ecosystems as well as sustainable use of ecosystem goods and services by man. Green roofs and greening of vertical walls can be considered as an example of ecological engineering. In this paper they will be dealt with in further detail.

Green roofs

The building of green roofs is becoming a good practice in a lot of countries in Europe, especially in Germany and the USA (Osmundson, 1999). In the Netherlands many small scale projects have been realized (Teeuw et al., 1997) but large scale implementation takes much more effort. In a report published by the municipality of Rotterdam (Anonymus, 2007) a survey is given about the different types of green roofs with full financial details. Comparison of different types was needed to stimulate large scale application including a proposal for a system of subsidies (Anonymus, 2007).

The advantages of vegetation on roofs are clear:

- Increase of water buffering capacity.
- Less runoff due to use by plants, transpiration and evaporation.
- Decrease of the amount of water in the sewer system (reducing cleaning costs).
- Improvement of air quality (deposition of particulate matter on leaves for example).
- Reduction of the heat island effect in urban areas.
- Energy savings (increase of insulation capacity; keep building cool in summer and keep cold out in winter).
- Noise level reduction up to 10 dB(A).
- Increase of lifetime of roofing material.
- Increase of aesthetic values.
- Increase of ecological values.
- Higher selling price of buildings.

A range of different types of designs are now available and realized: from very extensive (ecological roof, Sedum roof) till intensive roofs (garden and parks).

Greening of outside walls of buildings

The same advantages of vegetation on roofs can be described for greening systems on walls. In recent years different systems (figure 4.2.1) have been developed, like greening direct on the wall, greening systems before the wall and greening possibilities incorporated within the construction of the wall (Hendriks, 2008). Despite the range of possibilities there is still great hesitation in the building sector (from the originator, designer, architect till the builder and the user) to increase the amount of outdoor wall greening. Probably mainly due to the possible disadvantages: the need for extra maintenance, falling of leaves, chance of damaging the wall structure, increase of the amount of insect and spiders in the house and the expected extra costs involved.

Figure 4.2.1 Different types of façade greening (according to Hermy et al., 2005).

By allowing and encouraging plants to grow on walls the natural environment is being extended into urban areas; the natural habitats of cliff and rock slopes are simulated by brick and concrete. There is a widespread belief that plants are harmful to building structures, ripping out mortar and prising apart joints with their roots. The evidence suggests that these problems have been greatly exaggerated, except where decay has already set in and plants can accelerate the process of deterioration by the growing process (Johnston et al., 2004). Certainly there is little evidence that plants damage walls. In most cases the exact opposite is true, with plant cover protecting the wall from the elements. Ancient walls still stand, despite centuries of plant growth.

The leaves of climbing plants on walls provide a large surface area which is capable of filtering out dust (particulate matter PM_x) and other pollutants such as NO_x and taking up of CO_2 in daytime. Hard surfaces of concrete and glass encourage runoff of rainwater into the sewage system. Plants hold water on their leaf surfaces longer than materials and the processes of transpiration and evaporation, can add more water into the air. The result of this is a more pleasant climate in the urban area.
Vegetation provides also nesting places for birds such as, blackbirds, song thrushes and house sparrows. Particular species such as common ivy (*Hedera helix*) and for example climbing roses (*Rosa*) produce colourful berries enjoyed by birds in winter time.

Ecosystem functions, goods and services
One of the solutions to overcome the negative approach may be a change in the approach when assessing the environmental impacts: not only to look at the negative impacts of buildings on a site (as is common in environmental impact assessments), but to include positive values in the form of so-called ecosystem services of green roofs and green walls as well. Beside the positive effects of greening of walls the valuation should also include the greening of roofs and the greening of the surroundings as part of the ecological infrastructure on different scale levels to be seen as ecosystem service towards human society.
When we look at the façades or outside walls of buildings, green systems will show ecosystem characteristics, it will function like a habitat, will show structure, material and energy flows. But it will also provide ecological services like breeding and resting habitat for birds which may be enjoyed by humans, it will give extra insulation (reduced energy consumption in winter as well as summer), interception of rainwater, reducing air pollution (uptake of NO_x and particulate matter PM_x), reduction of noise level as well as change of perception of noise and increasing aesthetic value. Even it can give ecosystem goods like different kind of fruits for human use.

Vegetation, Particulate matter (PM_x) and aerosol deposition
In recent years there has been much interest in the health implications of fine particles in the atmosphere. Particulate matter of an aerodynamic diameter of less than 10 µm (PM_{10}) has become the standard measure of this form of air

pollution. Atmospheric particles, especially those with an aerodynamic diameter of <10 µm (the smaller particles of the $PM_{2,5}$ size range are considered as the most damaging to health, since they can more easily penetrate the respiratory tract.), pose a long-term threat to the human health, in particular to human respiratory functions. In the Netherlands the National Institute for Public Health and the Environment (RIVM) calculated that in the Netherlands approximately 18.000 thousand people die prematurely by the causes of particulate matter.
Particles are removed from the atmosphere by dry and/or wet deposition (Fowler et al., 2001). The dry deposition is the removal of pollutants by gravitational settling, impaction and interception. Vegetation is an efficient scavenger of particulate matter. Particle collection is due to the interaction of particles with vegetation surface (leaves, trunks and twigs). Vegetation has a large collecting surface area and also promotes vertical transport by enhancing turbulence, so there is a greater opportunity for particles to be collected on the vegetation surface. Applying living walls as a sink for air polluting substances leads to a contribution of better air and ecological quality.

One of the most common vegetation on walls is common ivy (*Hedera helix*). Common ivy is a strong evergreen climbing plant, growing up to 20-30 m high and commonly used as a cover on walls. Figure 4.2.2 show a leaf from the species *Hedera helix* with several (fine) particles on it. Interception of particulate matter happens not only on the upper side of the leave but also at the backside of the leave. Further research takes place at the moment, to get more insight in the relation between the particulate matter on the leaves, especially the difference between particle size distribution on the upper- and backside of the leaves.

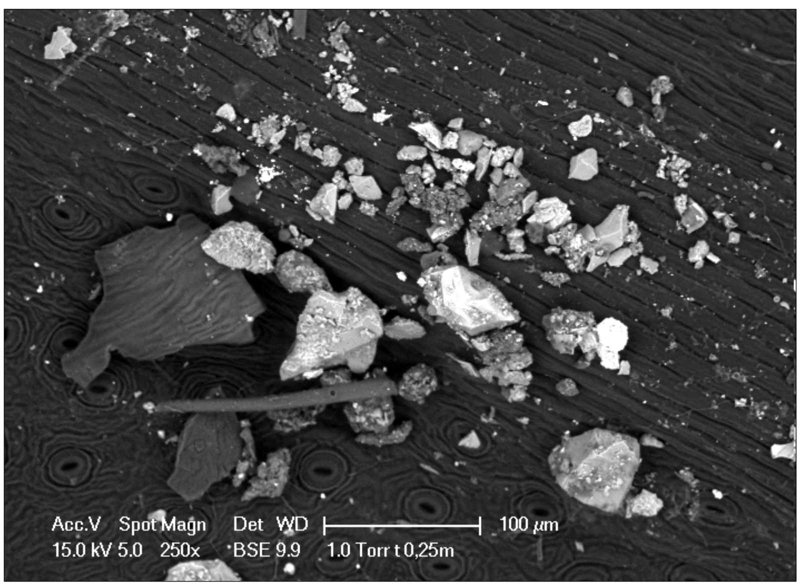

Figure 4.2.2 ESEM/BSE photomicrograph of particles on the backside of a leave of Hedera helix taken from the forest.

When we compare leaves of *Hedera helix* taken near a road with leaves picked in the woods we can see differences in the composition of the particulate matter (the ratio between anthropogenic source and the natural source of particulate matter). The particles on the leaves consist of a mixture of natural and anthropogenic sources. According to Beckett (1998) the finer $PM_{2,5}$ components are almost all particles come from anthropogenic sources. In the urban environment as much as 80% of emissions of these health damaging particles can come from road traffic. Figure 4.2.3 shows a photograph of parts of a *Hedera helix* leave taken near a traffic road (N259) with metal components on it (metal components probably coming free by friction processes of the moving cars, so one can speak about anthropogenic particulate matter (human origin)). Although the shown particle is classified as $\geq PM_{10}$ one can imagine that these particles can be broken down into smaller particles due to grinding processes. The chemical composition of the metal is given in Table 4.2.1 and figure 4.2.4 and is typically for stainless steel.

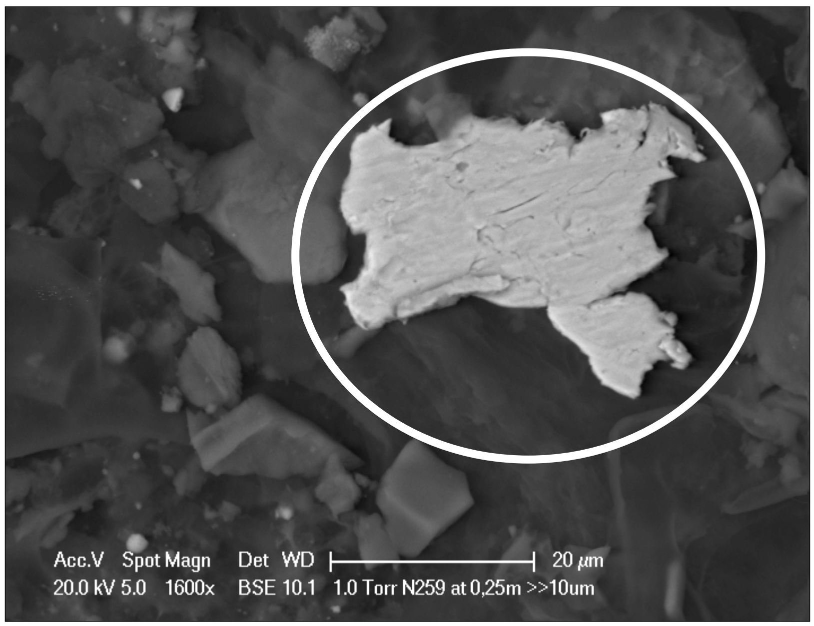

Figure 4.2.3 ESEM/BSE photomicrograph of particles on Hedera helix near a traffic road.

Table 4.2.1 EDX analysis of fractured (encircled) particle.

Element	Wt %	At %
C	19.49	45.48
O	10.55	18.49
Si	2.24	2.24
Mo	1.99	0.58
Cr	11.06	5.96
Mn	1.20	0.61
Fe	45.95	23.06
Ni	7.51	3.58
Total	100	100

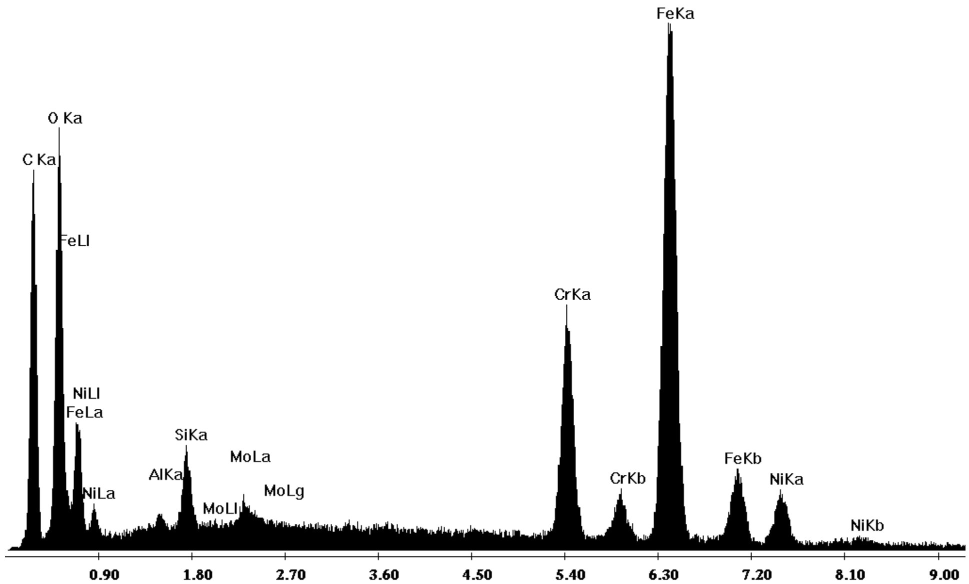

Figure 4.2.4 EDX-spectrum belonging to lightened particle in figure 4.2.2.

A visual assessment of the particles on the collected leaves was carried out using the environmental scanning electron microscope (ESEM). To distinguish the difference between the particulate matter on the leaves which are taken near the road and the wood, photographs where taken in a random order with different magnifications (100x, 250x and 500x). In addition, the cross sectional diameters of each of the particles were calculated with analyzing software to classify the size and calculate the total number of particles.

Preliminary results of this analysis confirmed that a larger amount of particulate material was in the category of particles smaller than 10µm (PM_{10}). With regard to the diameter of the particles, almost all the peaks where found in the range of 0 to 4 µm.

Using the elemental analysis (EDX) in the environmental scanning electron microscope, gives more insight in the chemical composition of the particles adhered on the leaves. The results of this analysis show that the most abundant element found on the leaves was Si and Fe. Particularly Si is typical for natural particulate matter.

Resuspension of particles

After the deposition of particulate matter on the leaves there is a chance that in dry and windy periods the particulate matter is again blown into the air, this effect is known as resuspension and it is estimated that the resuspension can be 50% of the scavenging particles (Nowak, et al., 1994). When the leaves are exposed to a rain wash, the particulate matter runs off to the surface of the soil, or the particles concentrates on the tip of the leaves (dripping effect). This high concentration of particulate matter (in fact a layer of particles) is shown in figure 4.2.5, and was found after the investigation of several leaves after two months weather influences. It is not likely that this accumulation of particles leads to resuspension of particles into the air again. The photograph shows also the great sink opportunity of vegetation on air polluting substances like particulate matter.

Vegetation can act as an efficient biological filter, with respect to removing significant amounts of particulate pollution from the (urban) atmosphere. The effect of vegetation is not only restricted to particle collecting. Vegetation is also efficient in taken up other air polluting substances such as CO_2, NO_x and SO_2. Vegetation is also beneficial for the urban environment with improving the aesthetics and biodiversity (Whitford et al., 2001).

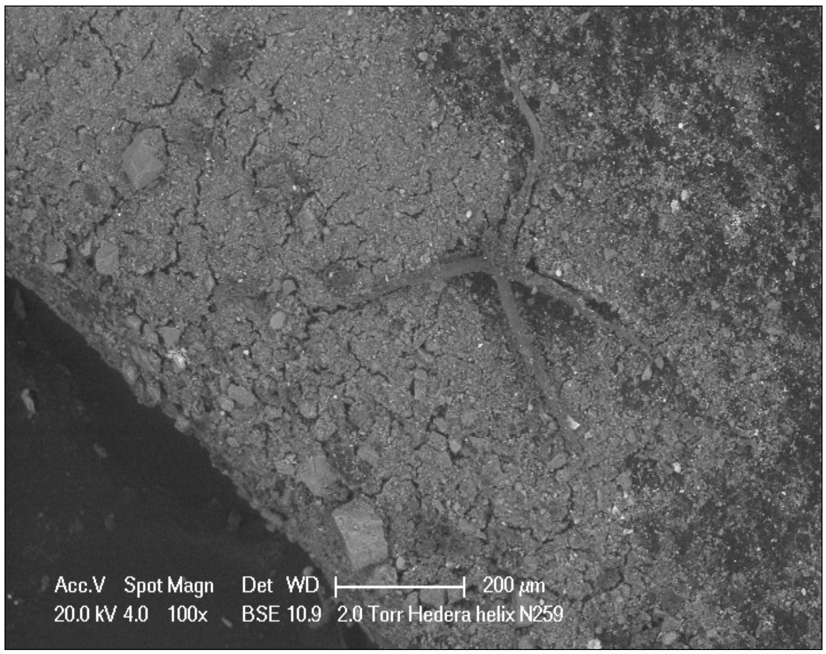

Figure 4.2.5 ESEM/BSE photograph of a high concentration of particles on a tip of a leave (Hedera helix) after a rain wash.

Comparison between outside walls within natural, more or less vertical habitats
Natural habitats of vertical situations, which are for example rocky habitats of mountain areas, rock outcrops, cliffs (inland or along the coast) of basalt, granite, limestone or sand. Lundholm (2007) worked on an urban cliff-hypothesis concerning the prediction that a large proposition of plants and animals living in urban habitats come from marginal rock outcrops or natural rock-based habitats.

Characteristic species of vertical situation are Sedum spec., lichens, mosses and algae. By enlarging the roughness of walls and by more different building materials (granite, limestone) the heterogeneity will increase and will give more plant species, especially more native ones, a possibility to grow, even shrubs and small trees. This will also increase the amount of micro-habitats for other plant species as well as birds and insects (bees, hoverflies, butterflies and spiders). At the same time we will increase the aesthetic value as well as an increase of air particles to settle down on vegetation. An interesting approach has been realized by the artist Hundertwasser with his wall greening of an apartment in Vienna.

The usefulness of this concept will also depend on the location on the world map (Table 4.2.2). From a nature conservation point of view it is relevant to look for native species as much as possible.

Table 4.2.2 Vertical natural habitats worldwide.

Habitat	**Type of vegetation**	**Location**
Granite outcrops	Different vegetation with endemics	Western Australia
Sea cliffs	Different maritime vegetation	Australia, U.K., France, Norway
Rock outcrops	Acid rock vegetation	South-Africa, Brasilia, Venezuela
Rocky ridges		Poland, Tsjechie, Slovakia
Inland cliffs	Limestone	U.K.

(From:Lundholm, 2007)

Artificial greening systems in urban areas

In recent years different innovative systems have been developed. Greening direct on the wall, greening systems placed before the wall and new greening possibilities incorporated within the construction of the wall (Hermy et al., 2005). However, despite this broad range of new possibilities, there is still hesitation in the architectural world and the building sector to increase the amount greening of outside walls. Probably due to the possible disadvantages like the need for extra maintenance, like falling of leaves, risk of damaging the wall structure, increase of insects and spiders, and probably the roofs extra costs too.

Improvements of green walls

The functioning of green walls can be optimized in a so-called integral "living" wall concept in which all relevant functions as well as ecosystem services are included in the design and building concept. The use of more native soil and native plant species will attract native organisms (bees, flies, hoverflies, butterflies, spiders, birds). The insects will give ecosystem service like pollination which is a great value for maintaining vital populations of plants.

For each building location first of all, we should find out the species composition of the site (genius locus) as well as the surroundings, so we know what we can find and also which organisms can be expected and in some cases stimulated.

Although hard-surfaces of concrete and asphalt are low in biodiversity the biodiversity can become enhanced by design. One of the possibilities is to increase the roughness of the surface it self till diversity of structure of construction within the wall by special open spaces, closed to the inside and (half) open to the outside filled with soil.

Even you can think of integration of walls as part of an integrated vertical bio-system for waste water treatment and production of vegetables.

Financial aspects

When considering financial aspects of green roofs it is important to include the long term costs and benefits as well. Nowadays the used sheets can be guaranteed for at least 40 years. When you compare the construction and maintenance costs of conventional flat roofs with extensive green flat roofs these will be not more expensive, but can be even cheaper than 'normal' asphalt roofs with gravel (Anonymus, 2007).

But other benefits of green roofs should be included as well: lower energy costs for heating and cooling, higher rental and selling rates of buildings, increase of aesthetic values, a better living environment for humans as well as plants and animals, less heat island effect in urban areas and filtering of air pollution. All these positive effects should be fully included in life cycle assessments and cost/benefit analyses.

Conclusions

Greening of roofs and outside walls of buildings have many advantages like lower heating and cooling costs, increase of aesthetic values, increase of ecological values, less heat island effect of urban areas and filtering of air pollution.

Vegetation can act as an efficient biological filter for removing significant amounts of particulate matter out of the (urban) atmosphere. There is a difference between the elemental composition of the captured particles on the leaves picked nearby a traffic road and taken in the wood. Most of the investigated particles appear to come from natural/geological sources (sand particles). And with respect to the particle distribution it can be concluded that the majority of the counted particles on the leaves are within the PM_{10} size, with a high concentration zone around the 0-4 μm fraction.

One of the solutions to overcome the hesitation by policy makers, planners, architects and inhabitants may be a change of approach in the planning and designing process of buildings. When assessing the potential of greening outside walls, we should not only look at the negative impacts of building as is common in environmental impact assessment, but we should include the positive values of so-called ecosystems services of green building fully as well. The problem is not only to build the correct greening on the wall, but also to organize the design and construction process; including the economical and social interaction with people living or that expects to live in the buildings in such a way that a more integral, balanced result will be the outcome!

4.3 Quantifying the deposition of particulate matter on climber vegetation on living walls

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M. Ottelé, H.D. van Bohemen and A.L.A. Fraaij
Delft University of Technology, Faculty of Civil Engineering and Geosciences, Stevinweg 1, 2628 CN Delft, P.O. Box 5048, The Netherlands. Corresponding author: M.Ottele@tudelft.nl, T +31 (0)15 2787439, F +31 (0)15 2786383

Abstract
The beneficial effect of vegetation on particle deposition is often stated in arboricultural literature but has rarely been researched in detail. To quantify these filtering effects of façade greening, it is necessary to study the accumulation properties of leaf surfaces on particle adsorption. In this paper attention will be given to a measure technique for particle adsorption on vegetation. The presented preliminary study aims to classify the total amount of particles by counting of particles on ESEM photographs. In the PhD research more attention will be given on the relation between particle reduction and the effect of vegetation on air quality improvements. Two locations were investigated, namely: leaves from near a traffic road and from a woodland. A difference in the particle amount was found at the underside and upper side of the leaves. For example, in a sampling at early autumn for the road location roughly 7000 particles (per 1275x950 μm) were count for the upper side respectively roughly 3200 particles for the underside. Also a difference in particle amount was found between the two different locations, respectively roughly 7000 particles for the upper side of the leaf at the road location and roughly 3300 for the woodland location. The comparison must give more insight in the sink capacity of vegetation, but also between the environments. In the paper, results of counting particles on leaves from both locations will be provided via a factorial design approach with four independent factors at two levels (height, leaf, time and environment). The outcome of the factorial design shows that there is a difference between the collecting capacity of the leaf (upper side/underside) and between the environments (road/woodland). Fine and ultra-fine particles (i.e., the fractions that are potentially the most harmful to human health) were more abundantly found on the leaves than coarser particles. Also some energy dispersive X-ray analysis (EDS) of the adhered particles will be provided. As main conclusion of this research can be said: that counting particles instead of weighing particles on a specific leaf area seems to be a proper way to classify aerosol deposition on vegetation.

Keywords: particulate matter (PM_x), living walls, façades, common ivy, *Hedera helix*, vertical greening, building surfaces, noise barrier, ecological engineering.

Introduction

Background

In recent decades living walls, vertical greenings of façades of buildings or noise barriers have been realized. Vertical greening offers an outstanding number of public and private benefits such as: aesthetical, social, ecological and environmental, and fits in the principle of ecological engineering as defined by Odum (1995). Therefore the vertical greening of commonly used building materials (concrete, brick, etc) can be an attractive tool to counteract the (local) air pollution. Vertical greening of façades has more potential to increase the particle collecting area of a building then only a green roof (for example: greening a façade of a cubical building encompasses four times the area of the roof). This paper in the framework of a PhD research on vertical greening, deals among other things with the possibility of air- and ecological quality improvements by the use of vertical greenery. Vertical green can be defined as the growing of plants directly on, or with the help of plant guiding constructions alongside the building façade. 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 vegetation. 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 (Köhler, 2008). Vertical greenery implies all suitable vegetation such as algae, lichens, herbaceous plants, climbing plants and small shrubs.

The presented experimental work investigates the adsorption of particulate matter on leaves near a traffic road (N259) in the Netherlands and leaves from the woodland. The species which has been investigated is the common ivy (*Hedera helix*). Common ivy is an evergreen climbing plant which grows easily up 20 to 30 m height and is commonly used as a cover on façades or on sound barriers.

Particles can be removed from the atmosphere by dry, wet or occult deposition (NEGTAP, 2001). Dry deposition is the removal of pollutants by sedimentation under gravity, diffusion processes (i.e. by Brownian motion) or by turbulent transfer resulting in impaction and interception (Becket et al., 2004). Vegetation is an efficient sink for particulate matter (Fowler et al., 1989). Particles from the air are mainly adhered to the outside of plants. This in contrast to air polluting gases and very small particles (< 0.1 μm) which are assimilated for an important part via the stomata into the leaves (Fowler, 2002). The efficiency on the collecting capacity of particles (aerosols/particulate matter) out of the air by vegetation depends on the following factors (Tonneijck and Blom-Zandstra, 2002; Wesseling et al., 2004):

- Plant variety (shape and surface of the leaves, deciduous or evergreen plants).

- Structure of the vegetation (width and altitude, roughness, porosity or penetrability).
- Exhibition (source of the component, exhibition level).
- Location (distance to the source of emission, presence of building structures).
- Circumstances (growing circumstances, micro-climate).

Particles are classified in fractions according to their size. The fractions are expressed in µm and refer to the maximum aerodynamic diameter of a spherical particle. The usual monitored size fraction is called PM_{10} (particles with an aerodynamic diameter smaller than 10 µm). Below PM_{10} the size range of particles found in the atmosphere is usually considered in three groups namely: coarse particles, fine particles and ultra-fine particles (Beckett et al 2004; NEGTAP, 2001).

In this preliminary research the removal of particulate matter out of the air has been chosen because atmospheric particles, especially those with an aerodynamic diameter of <10µm (PM_{10}), pose a long-term threat to the human health, mainly to the human respiratory functions (Pekkanen et al., 2000). The research investigates different parameters that can have an effect on particle adherence by vegetation. One of those parameters for example is the surrounding environment. Therefore leaves from nearby a traffic road and leaves from the woods were investigated in this research. Also other parameters are investigated; e.g. difference between the upper side and underside of the leaves, difference in picking height and difference between weather exposure or time effects.

Research techniques such as the Environmental Scanning Electron Microscopy (ESEM) and Energy Dispersive X-ray (EDS) analysis were used to classify particle size and particle distribution on the leaves and to characterize (the elemental composition) the particulate matter on the leaves.

Research questions

Since the objective of the PhD study is the improvement of the air quality and ecological value of green façades or noise barriers, this has lead to the formulation of this first sub- research with as objective: the development of a measure technique to count particle accumulation on leaves growing under certain circumstances and environments.

Therefore the following research question(s) were formulated:

- How are we going to measure?
- Is there any difference perceptible with a counting method between leaves from the urban area or from the rural area on the total amount of particle adherence?

- Is there any difference on the adherence capacity between leaves of the same species on different heights?
- Is there any difference on particle adherence between the upper side and underside of the leaves?
- Is there any difference on particle adherence during exposure under weather influences (early autumn and late autumn)?

Because of the special interest in the capability of particle adherence by vegetation, the standard air quality measurements of particles in the air, that especially have been designed to control whether the concentration in the air exceeds the permitted value(s), seems not to be suitable. The approach to measure the mass of particles collected on the leaves ignores the actual amount of the total particle collecting on leaves. Since the particle size is positively correlated with lung diseases it is important to know how many of those fine or ultra fine particles are adhered on the leaf surface. Counting particles on a specific leaf area seems therefore more suitable for this experiment.

From the literature (NEGTAP, 2001) it is known that concentrated emitting sources will influence the deposition of air pollution substances. The leaves that are examined in this experiment to classify and characterize the particulate matter are therefore coming from two different locations namely:

- Leaves of *Hedera helix* picked on a sound barrier (figure 4.3.1a) near a local traffic road (N259) near Bergen op Zoom in the Netherlands. For this location we expect more particles in the air, because there is an emitting source (the driving cars) very closely to the vegetation.
- Leaves of *Hedera helix* picked in the woods (figure 4.3.1b) near Bergen op Zoom in the Netherlands. For this location we expect fewer particles on the leaves, because no direct emitting sources are present in the surrounding.

Figure 4.3.1 For sampling used road (photo a) and woodland (photo b) location.

The chosen green façade (in this case a sound barrier) for investigation is situated directly near an intensively used cargo transport road (N259). Near the side of the green façade/sound barrier also a traffic light installation is present.

The observed growing strength and overall condition of the vegetation is very well. Also the covering of the façade is entirely over the full height (+/- 2.5 m). The planting is mainly at the roadside and only the traffic side is monitored in this experiment. The observed sound barrier is located on the south side and stands parallel to the road. The façade stands approximately 4 meters out of the road axis and 1 meter from the verge.
The wood location is mainly shadowy due to the canopies of the surrounding trees. The chosen ivy is climbing on a tree which gives the ivy the needed support to reach the canopy. The height of this tree is approximately 15 meters. The observed growing strength and overall condition of the vegetation is very well.

Because of the growing height and the possibility of application of vegetation on façades, also the height can play a role in the collecting capacity of vegetation. The sampling procedure of the leaves for this experiment was the same on both locations. Only complete green and full-grown leaves of the leaf surface were chosen, and only leaves with an angle of approximately 45 degrees relative to the vertical wall have been picked. In this experiment a distinction was made between the picking heights, respectively 0.25 m, 1.50 m and 2.50 m from ground level, see figure 4.3.2.

It is important to know which side of the leaf (upper side or underside) has the highest potential to adhere particles. Not only the amount of captured particles per leaf side is important but also differences in particle sizes per leaf side. In this experiment the upper side and underside of the leaves were examined to make a distinction between the two sides.

Particles can be re-suspended or washed off (Powe, 2003; Nowak et al., 1994). So natural weather influences such as rainfall and wind can have an effect on the collecting capacity of vegetation, but the question is: are we able to quantify these effects? In this research also the seasonal impact (early autumn and late autumn) on the collecting capacity is investigated.

Methods

Experimental description

During the first sampling of a randomly chosen leaf, half of the leaf was removed. The remaining part of the leaf was removed during the second sampling period as is schematically given in figure 4.3.2. This approach was chosen to examine the possible seasonal impact on the collecting capacity and to make use of the statistical paired test. The removed plant material was sealed and labelled separately in plastic containers to exclude the possibility of contamination after sampling. This approach secures that the leaf will be totally untouched until the examination in the Microlab of Delft University of Technology. Investigation of the used plastic containers before and after sampling shows that no particles were lost (falling off) during the sampling. The plant material out of the wood was handled in the same way as the samples from the traffic road, and will be used as a reference to see if there will be any interaction or differences between the environments. Per picking height two leaves were chosen and examined in this experiment.

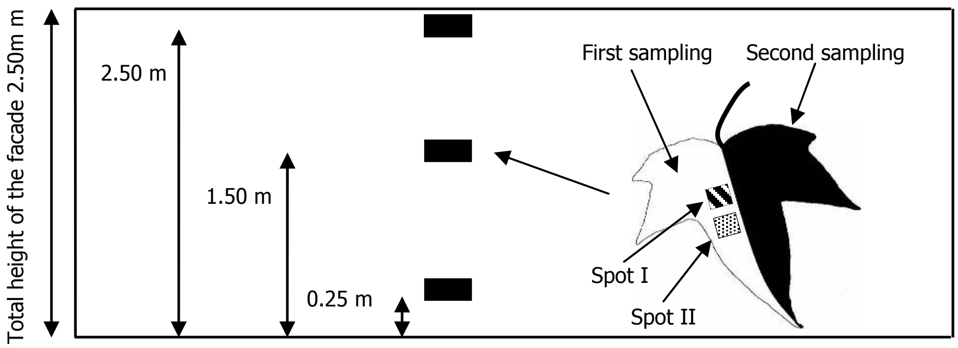

Figure 4.3.2 Side-view of the sound barrier near the traffic road with vegetation (Hedera helix) from which samples were taken at different heights.

After the plant material was collected and archived the leaves were prepared to investigate. Therefore systematically in the middle of the central axis (nerve) two samples of 1x1 cm^2 are cut, schematically presented by spot I and spot II in figure 4.3.2. One sample will be investigated on the upper side of the leaf, respectively the other sample will be investigated on the underside in a random order. After the sampling a visual assessment of the leaves was carried out in the ESEM. In the ESEM we can use the sample as received. No gold or carbon sputtering is necessary; because in low vacuum (no drying) and wet mode no electrical conductivity of the sample is facilitated (the plant material exists also from carbon). To investigate the elemental composition of the particles on the leaves the EDS-analysis or elemental-mapping technique was carried out on with Philips XL30 ESEM with a tungsten filament. The EDX system is by EDAX with a super ultra thin window (version 3.3) and a resolution of 128.0 eV. The lower detection limits are 0.01 wt.% for all element species.

Particle Analysis

To distinguish the difference between the amount of particulate matter on the leaves (the upper side and underside of the leaf) picked near the road and the wood, photographs where taken with the electron microscope on a randomly chosen spot with a reasonable particle distribution (not clogged and between the leaf nerves) at a magnification of 100x on the 1 cm^2 sample. When such a region is found the spot is fixed in the middle of the view and the micrographs are taken. This procedure was repeated for the second and third photo series. The micrographs are taken with different magnifications, namely 100x, 250x and 500x.

After collecting microphotographs the particle counting was done automatically with a software package called *Image J*. Particle analysis requires that the image is a "binary" image (i.e. black or white). The biggest issue is to distinguish the particles from the background (threshold). See figures 4.3.3a and 4.3.3b to go from raw to threshold. For this analysis we make use of the automatic thresholding function in *Image J*. Setting a threshold manually will introduce a user-bias in the analysis, therefore the automatic threshold function used by Image J was applied. Further information about the program can be found on http://rsbweb.nih.gov/ij/.

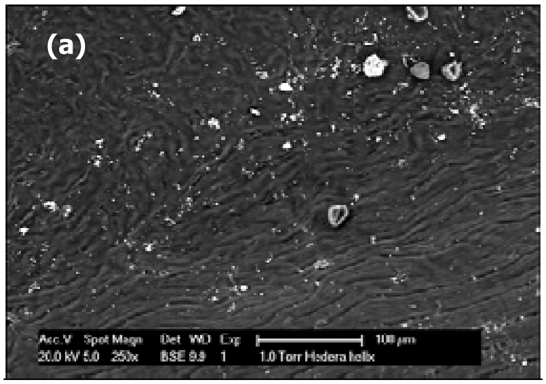

Figure 4.3.3a ESEM/BSE micrograph of particulate matter on Hedera helix (upper side of the leave) before thresholding.

Particles that are slightly overlapping in a threshold image have to be separated; this was done with the watershed function in *Image J*. The watershed function is schematically processed in figure 4.3.4. Once the particles have been successfully threshold and watershed, they can be analyzed to obtain information regarding particle size and numbers. In the analysis no boundary to the circularity value was given (i.e. a value of 1.0 indicates a perfect circle), which means that all various shapes of particles were count.

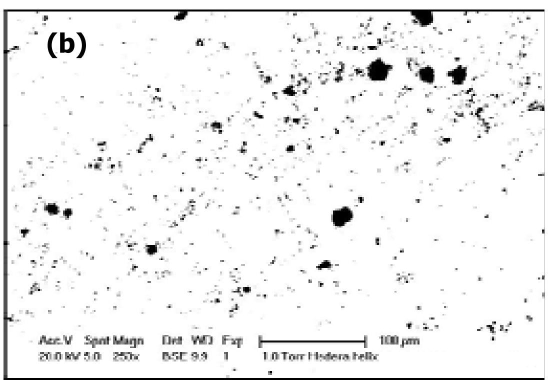

Figure 4.3.3b ESEM/BSE micrograph of particulate matter on Hedera helix (upper side of the leave) before thresholding.

Per magnification different particle sizes were counted: for 100x particles >10 µm, for 250x particles ≤ 10 and ≥ 2.5 µm and for 500x particles between ≥ 0.2 and < 2.5 µm. Also weighing factors, respectively 6.25 and 25 times, were used for the magnifications 250x and 500x to compensate for the loss of counting area (zoom effect). In addition, the cross sectional diameters of each of the particles were calculated, assuming that a calculated area belongs to a certain aerodynamic diameter. The experiment and procedure for counting was repeated and carried out on the same way for the second sampling period.

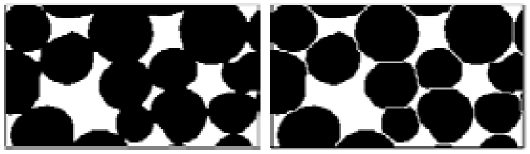

Figure 4.3.4 Principle of watershed segmentation (source Image J).

To understand the relations between the independent parameters in this experiment the data was statistically processed into a factorial design, which makes it possible to study the effect of each of the independent factor(s) on the response variable (i.e. counted particles), as well as the effect of interactions between factors on the response variable.
The outcome of the factorial design will be used for the set-up of further experiments concerning particulate matter and the collecting capacity of vegetation. The factorial design for this experiment was built up with 4 factors at 2 levels per factor and is schematically given in table 4.3.1.

Table 4.3.1 Schematic representation of the used independent parameters and the definition of the two levels in the factorial design diagram.

Parameter	**Low level**	**High level**
Height	(a) 0.25 m from ground level (abcd)	(A) 2.50 from ground level
Leaf	(b) Upper side	(B) Underside
Time	(c) Early autumn	(C) Late autumn
Environment	(d) Traffic road	(D) Wood (ABCD)

The outcome of the factorial design will give more insight into the relevance and interactions between the different main parameters and also enables H_o hypothesis checking. The null hypotheses are:

- $H_{ø1}$: no main effect of the height (coded as low level (a) respectively high level (A)).
- $H_{ø2}$: no main effect of leaf side (coded as low level (b) respectively high level (B)).
- $H_{ø3}$: no main effect of time (coded as low level (c) respectively high level (C)).
- $H_{ø4}$: no main effect of the environment (coded as low level (d) respectively high level (D)).
- $H_{øn}$: no main effect of interaction between any two individual parameters.

The results of counting particles are given in table 4.3.2 with the different factorial combinations and accompanying data.

Table 4.3.2 Factorial design combinations with analyzed data series counted on 1275x950 μm^2 of leaf area. The table gives the number of counted particles.

Particle size	≤ 1.5 µm		2.5-4 µm	
Notation	*sample 1*	*sample 2*	*sample 1*	*sample 2*
abcd	4279	11250	426	511
Abcd	10673	5769	341	341
aBcd	19135	8558	909	1108
ABcd	20673	23942	398	1364
abCd	10481	8846	1307	739
AbCd	16298	18750	625	1136
aBCd	24135	23654	1193	2045
ABCd	4288	22212	625	966
abcD	971	2948	74	432
AbcD	3337	3029	284	426
aBcD	9760	7260	625	1790
ABcD	9808	5481	341	1420
abCD	8750	1577	795	114
AbCD	1346	3942	142	994
aBCD	8846	3221	483	540
ABCD	13702	7067	1591	909

Results

Outcome elemental analysis

The results of the EDS analysis shows that the most abundant elements found on the leaves were Ca, Si and Fe. The high carbon contents in table 4.3.3 are due to the leaf composition. For the samples taken near the road also amounts of fly-ash particles and the elements Ti, S, F, Al and Cu have been found. Also several stainless steel particles with a wide range of size and shape were found. Figure 4.3.5a shows the shape of one of such a stainless steel particle. The chemical composition of the metal is given in table 4.3.3 and is typical for some stainless steels. To get an idea of the composition of the particles, several EDAX scans were made and one of those scans is given in table 4.3.3 for the encircled particle in figure 4.3.5b.

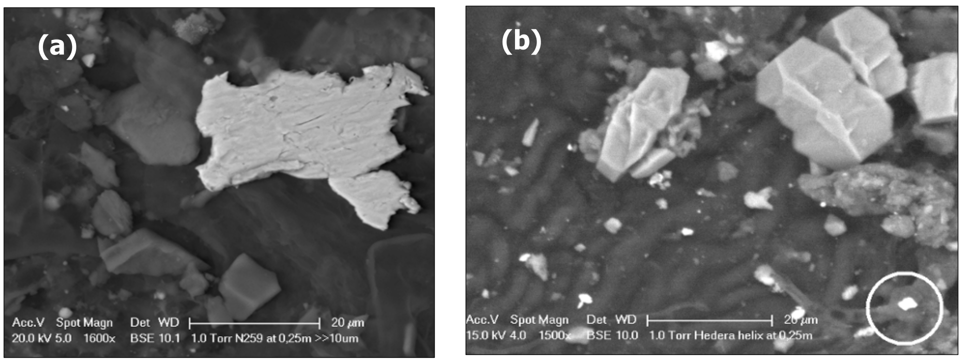

Figure 4.3.5 ESEM/BSE micrograph of stainless steel particle (a) and several fine particles (b) found on Hedera helix leaves near a road.

Table 4.3.3 EDS analyses belonging to figures 4.3.5a, b and 4.3.6a. The high carbon content is from the leaf surface.

	EDS analysis					
	Figure 5a		Figure 5b		Figure 6a	
Element	*Wt %*	*At %*	*Wt %*	*At %*	*Wt %*	*At %*
C	19.49	45.48	58.60	69.14	54.33	85.90
O	10.55	18.49	28.06	24.86	8.77	10.41
Si	2.24	2.24	4.80	2.42	0.52	0.35
Fe	45.95	23.06	2.68	0.68	-	-
Ca	-	-	0.54	0.19	-	-
K	-	-	0.67	0.24	-	-
Al	-	-	4.11	2.16	-	-
Mg	-	-	0.54	0.31	-	-
Mn	1.20	0.61	-	-	-	-
Ni	7.51	3.58	-	-	-	-
Cr	11.06	5.96	-	-	-	-
Mo	1.99	0.58	-	-	-	-
Pb	-	-	-	-	36.37	3.33
Total	100	100	100	100	100	100

Worth mentioning is that only one time a lead particle (figure 4.3.6b) of 20 µm was found on a leave from near the traffic road. Remarkable is that only on the leaves from the woodland location, organisms (figure 4.3.6a) were detected. Mostly the organisms were found on the underside of the leaf. Organic compounds were detected on both of the sample locations.

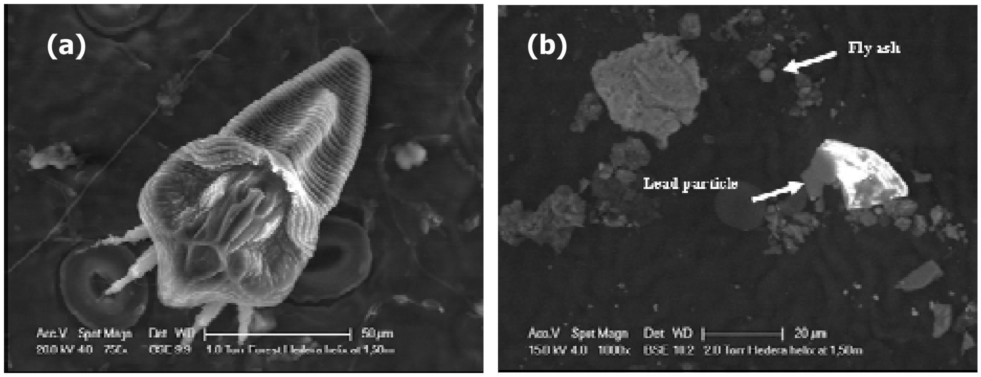

Figure 4.3.6 ESEM/BSE micrograph of found organism (photo a) on a Hedera helix leaf from the woodland and a lead particle (photo b) found on a leaf near the road.

<u>*Outcome of counting particles*</u>

The result of counting particles on a specific leaf area (950x1275 µm^2) results in a particle size distribution (figures 4.3.7a and b) for the underside and upper side of the leaves. Particles ≥ 10 µm appeared to be rather rare compared to particles ≤ 10 µm. The particles larger than 10 µm are therefore negligible and will not be studied. Almost all the intensive peaks were found in the range up to 4 µm. The smallest particles that could be counted with the applied measurement technique are in the range of 0.2 µm.

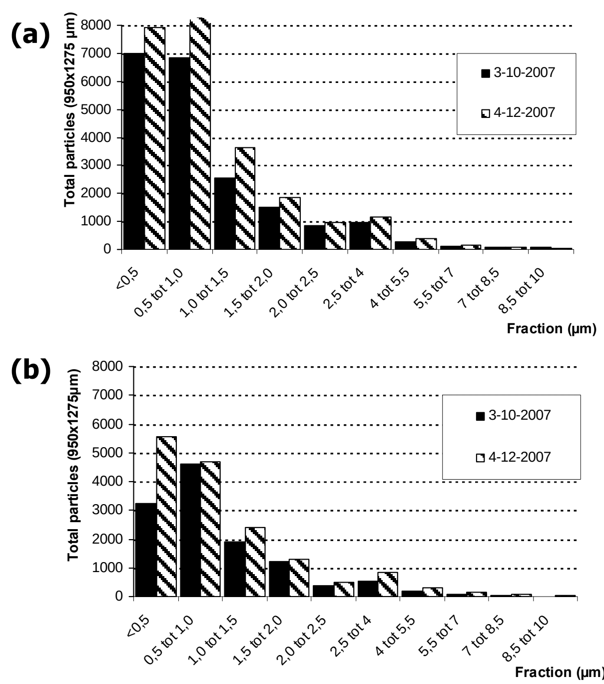

Figure 4.3.7a Total average of particle size distribution for upper side (a) and (b) underside of the leaves near the road location (N259).

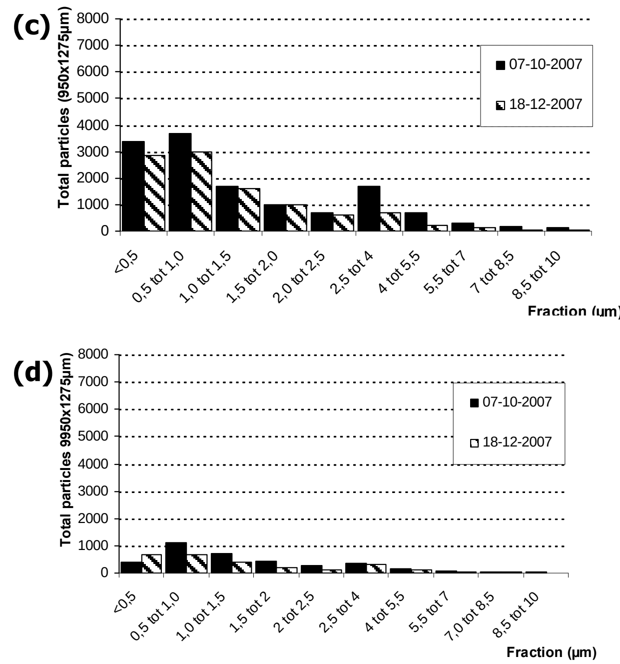

Figure 4.3.7b Total average of particle size distribution for upper side (c) and (d) underside of the leaves for the woodland location.

Outcome statistical analysis

The outcome of the statistical analysis shows that in this specific situation, for particle size ≤ 1.5 µm no relation between the different picking heights (factor coded as A in table 4.3.4) can been found, the null hypothesis is thus accepted. The low F_0 value and the high P-value (table 4.3.4) confirms that the hypothesis is accepted for alpha = 0.05.

Between the upper side and underside of the leaf (factor coded as B in table 4.3.4) a significant difference in the total amount of collected and counted particles are observed. Table 4.3.4 gives a high F_0 value and a low P-value; this means that the null hypothesis is rejected. On the upper side of the leaf a larger amount of particles was counted (roughly two times more particles on the upper side) in contrast with the underside of the leaf (particles larger than 10 µm are only found on the upper side of the leaves). It appeared that there is no significant difference between the two examined picking dates (code C), there is however a significant difference between the counted particles on the leaves coming from the traffic road and leaves coming from the wood. Leaves from the traffic road collected a larger amount of particles than leaves from the wood. For code D therefore we found a high F_0 value and a low P-value which means that the null hypothesis for the road and the wood is rejected.

Because of the very low contribution (<5%) of the double interactions compared with the other interactions, the triple interactions are ignored in this analysis.

It was remarkable that as well for leaves picked near the traffic road as for leaves from the wood the peak of 2.5-4 µm was higher than the surrounding fractions. However further investigation of this fraction with the EDAX showed that the majority of the particles with this aerodynamic diameter consists of the elements Si, Al and Fe, which is however the same as with the other fractions.

Table 4.3.4 Outcome statistical analysis factorial design scheme.

Outcome factorial design one sided alpha of 0.05 and triple interactions ignored			particles ≤ 1.5 µm			particles 2.5-4 µm		
Name	Model term	Coded	F0	P-Value	Contribution (%)	F0	P-Value	Contribution (%)
Height (low/high)	1	A	0,30397	0,5872	0,5%	0,21716	0,6460	0,6%
Leaf (upper/under-side)	2	B	10,8568	0,0035	18,9%	8,94026	0,0070	23,2%
Time (early/late autumn)	3	C	1,0032	0,3279	1,7%	1,79573	0,1945	4,7%
Environment (road/wood)	4	D	22,083	0,0001	38,4%	1,45508	0,2411	3,8%
	1,2	AB	0,14345	0,7087	0,2%	0,14537	0,7068	0,4%
	1,3	AC	0,45892	0,5055	0,8%	0,08273	0,7764	0,2%
	1,4	AD	0,06828	0,7964	0,1%	2,10695	0,1614	5,5%
	2,3	BC	0,69786	0,4129	1,2%	1,05656	0,3157	2,7%
	2,4	BD	0,48393	0,4943	0,8%	0,24282	0,6273	0,6%
	3,4	CD	0,37637	0,5461	0,7%	1,44434	0,2428	3,8%

In figure 4.3.8a the data points (32 measurements) are reflected against the normalized distribution with triple interactions ignored.
For the fractions 2.5-4 µm also a statistical analysis was carried out. Code B in table 4.3.4 gives a high F_0 value and a low P-value, which means that the null hypothesis is rejected. Compared with the analysis of particle size ≤ 0.5 µm, now the environment (code D) has no influence. Because of the very low contribution (<5%) of the triple interactions compared with the other interactions, in figure 4.3.8b the data points (32 measurements) are reflected against the normalized distribution with triple interactions ignored.

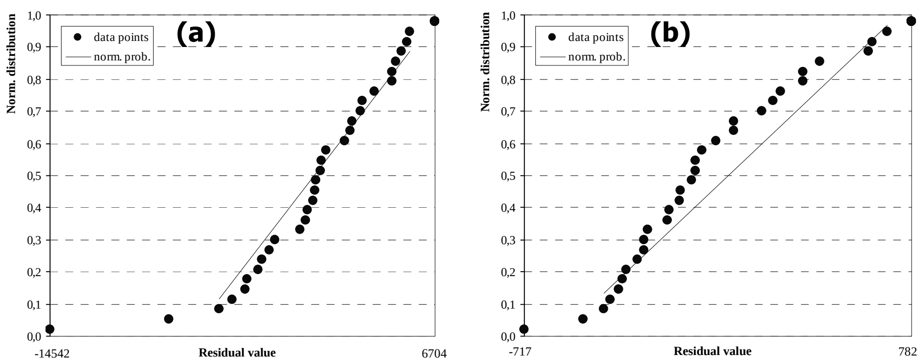

Figure 4.3.8 Data points compared with the normalized distribution for particle size ≤ 1.5 µm (a) and for particle size 2.5-4 µm (b).

Discussion

When we compare leaves of *Hedera helix* taken near a road with leaves picked in the wood we see differences in the chemical composition of the particulate matter (the ratio between anthropogenic source and the natural source of particulate matter). The particles on the leaves show a mixture of natural and anthropogenic sources. According to Beckett (1998) the finer $PM_{2.5}$ components are almost all particles coming from anthropogenic sources. In the urban environment as much as 80% of emissions of these health damaging particles can come from road traffic. On the leaves a huge amount of (ultra)fine particles were counted. The striking peak of the fraction 2.5-4 μm contains mainly Si, Al and Fe; these components are also related to mineral dust or soil components (Chow et al., 1996; Matthijsen and Visser, 2006). The fact that this peak is found for the road as well as for the woods, confirms that these particles can be coming from the (cross-border) background concentration which may also induce an amount of natural compounds. The stainless steel particles (metal components probably coming from friction processes of the driving cars, so one can speak about anthropogenic particulate matter) are also from human origin. Although the shown particle in figure 4.3.5a is classified as $\geq PM_{10}$ one can imagine that these particles can be broken down into smaller particles ($\leq PM_{10}$) due to grinding processes for example by the driving cars. Due to the air vortexes caused by the driving cars these particles can be blown into the air again. The stainless steel particles are only found on leaves near the road. Since these particles are from human origin this shows that vegetation can collect particles from a close emitting source, this in contrast with the particles found on leaves coming from the wood. Vegetation therefore can be seen as a particle scavenger if it is placed for example closely by an emission source but it can also be used to lower the background concentration of air polluting substances.

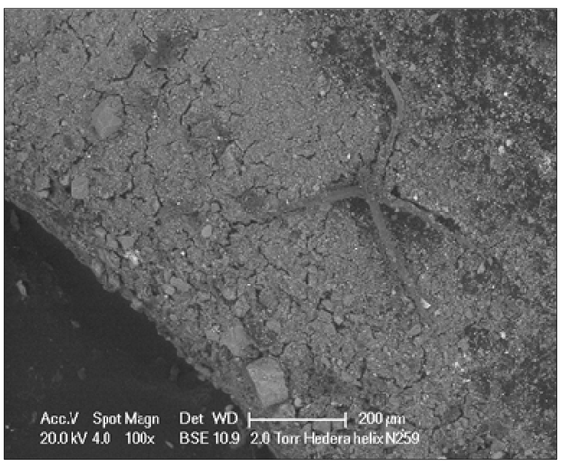

Figure 4.3.9 Clogged particles on the tip of a leaf after two months weather exposure.

After the (dry or wet) deposition of particulate matter on the leaves there is a chance that in dry and windy periods the particulate matter is blown into the air again, this effect is known as resuspension and it is estimated that the resuspension can be 50% of the absorbed particles (Nowak et al., 1994). When the leaves are exposed to a rain wash, the particulate matter runs off to the surface of the soil, or the particles concentrates on the tip of the leaves (dripping effect). This high concentration of particulate matter (in fact a layer of particles) is shown in figure 4.3.9, and was found after the investigation of several leaves after two months weather influences. It is not likely that this form of accumulation leads to resuspension. The microphotograph shows also a sink opportunity of vegetation on air polluting substances like particulate matter.

It can be concluded that the picking height has no influence (null hypothesis is not rejected). However, wind turbulences can have effect on the deposition of particulate matter. Thönnessen (2002) has shown, that the highest amount of heavy is found near the emission source, directly beside the road. In the height of 7.5 m a second maximum was found at a lower level. This is only found in urban street canyons. Thönnessen (1996) showed at seven different locations in the urban area of Düsseldorf that the highest heavy metal concentrations were always near the traffic emission height. Sound barriers are mostly restricted to a certain height so probably greening façades to a larger height can work beneficial on collecting particulate matter out of the air. The difference between the amounts of particles counted on the upper side and underside can be explained by the difference in deposition chance of particles and through wind turbulences. Although also the underside of the leaf contains particles, the upper side of the leaf will collect more particles. For the total aerosol collecting capacity of a leaf it is important to take both sides of the leave into account.

The capability in which for example self clinging plants are able to adsorb particles is positively related with the leaf area index (m^2/m^2). *Hedera helix* for example has 2.6 up to 7.7 m^2 leaf/m^2 wall (Bartfelder and Köhler, 1987). With the achieved data of counting particles, this results in an enormous amount of particles per square meter leaf. It can be estimated for the road, that the total amount of particles (upper side and underside) is about $1.47x10^{10}$ particles per m^2 leaf area; respectively for the wood location $8.72x10^9$ particles per m^2 leaf area.

However can vegetation really remove particles out of the air? Or is it only because we measured on the right time and place? This, because the time effect or exposure time to weather influences showed no significant difference in the total amount of particles on the other half of the examined leaf. Is it possible that during rainfall particles will flush away and what is the effect on particle collection? Or has rain not that influence on the purifying capacity (lotus effect) of the leaf to carry away the particles to surface level where it can disappear in the soil? Leaf research on resuspension in combination with weather influences on the leaves is therefore recommended. Also the link to particle concentration in the air and the potential reduction of the concentration by vegetation must be coupled, this for calculating the total effect of vertical greening for improving (local) air quality. Further experiments are necessary to investigate these questions and to understand the mechanisms behind vegetation and particle adherence.

Vegetation is not only restricted to particle adherence it is also efficient in taking up other air polluting substances then particulate matter such as CO_2, NO_x and SO_2 (Miyawaki, 1998). It should be realized that vegetation is also beneficial for the urban environment with improving for example the aesthetics and biodiversity (Whitford et al., 2001) but also to counteract the urban heat island effect (Gomez et al., 1997). Therefore vertical greening or living wall concepts will be a good principle to use in the urban area to improve the air and ecological quality.

Conclusions

Since the research was focused on counting fine dust particles on leaves and between different circumstances, the main conclusions that can be drawn from the presented results on particulate matter and vegetation are as follows:

- Leaves form a sink for significant quantities of health-damaging particles from the atmosphere, with the potential to improve local air quality.
- There is a great difference on particle adsorption between leaves taken near a road and from the woods (urban area versus rural area).
- All investigated leaves captured three size ranges of particulate matter (coarse, fine and ultra-fine) according to Beckett, 2004.
- The upper side of the leaf collects more particles than the underside of the leaf.
- No significant difference was found in this research between the sampling heights in this situation.
- No significant difference was found between the two sampling dates.
- Vegetation is able to collect PM_{10} particles, especially the fine and ultra fine particles are in the majority, respectively roughly 7000 ultra fine particles (per 1275x950 μm) were count on the upper side of the leaf at the beginning of the season and more than roughly 8000 of particles were count at the end of the season. Counting instead of weighting particles on a specific leaf area seems to be a proper way to classify aerosol deposition on vegetation.

Acknowledgements

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4.4 The development of an ESEM based counting method for fine dust particles and a philosophy behind the background of particle adsorption on leaves

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M. Ottelé[1], W.N.J. Ursem[2], A.L.A. Fraaij[1] and H.D. van Bohemen[1]

[1] Faculty of Civil Engineering and Geosciences, Delft University of Technology
[2] Department of Biotechnology-section Botanic Garden, Faculty of Applied Sciences, Delft University of Technology
Stevinweg 1, 2628 CN Delft, P.O. Box 5048, The Netherlands.
Corresponding authors: M.Ottele@Tudelft.nl, W.N.J.Ursem@Tudelft.nl

Abstract
The multi scale benefits of urban greenery (green façades and green roofs) gets in more and more interest of recent research work. The multi scale benefits of vegetation vary from; mitigation of the urban heat island effect, stimulation of the ecological value and biodiversity, aesthetical reasons and for example air pollution reduction. Air pollution control is at the moment mainly focussed on the reduction of fine particle concentrations. Particulate air pollution is damaging for the human health, it causes cardiovascular and lung diseases. Especially dust particles smaller than 2.5 micrometers are of great interest because they can be deeply inhaled into the respiratory system. To determine the effect of leaves on particle adsorption micrographs are taken of ivy (*Hedera helix*) leaves using an Environmental Scanning Electron Microscope (ESEM). The examined leaves are exposed to a simulated rainfall in order to determine a method for particle counting on leaves and to determine the self cleaning effect of adsorbed particles on ivy leaves. The self cleaning effect is considered to be an important factor in the effectiveness of particle adsorption by leaves and the potential for resuspension of particles. Particles on pre- and post-rain leaves were count via the ESEM micrographs using an image analyzer. Results showed that there is no significant effect on particle loss due to rain in the performed experiment. Our findings suggest that a strong Van der Waals bonding between particle and leaf surface plays an important role in the retaining process of fine particles on the leaf surface.

Keywords: green façades, fine particle accumulation, environmental scanning electron microscopy, simulated rainfall, *Hedera helix*.

Introduction

Green façade designs offer numerous economic, social and environmental benefits such as greenhouse gas emission reduction, adaptation to climate change, air quality improvements, habitat provision and improved aesthetics. Also sound reductions are possible by the use of vegetation (Pal et al., 2000). Despite these benefits a widespread market penetration of greening technologies over the world remains still in its infancy. Greening the façades of urban buildings or infrastructural projects (i.e. sound barriers, tunnel alignments, etc.) using climbing plants or living wall systems (LWS) modifies the interaction of the building system with the surrounding atmosphere. For example: plants have the ability to dissipate absorbed solar radiation into sensible and latent heat (Stec et al., 2004). This is often related to the urban heat island effect, but it has also an effect on the vertical air velocity (Minke, 1982) and is thus (indirectly) related to particle deposition processes. With other words, a specific microclimate will be created around a green building envelope. This microclimate could not only improve the outdoor or indoor climate but will also have an effect on the distribution and accumulation of particles inside the street canyon due to the filtering capacity of climbing plants (Bruse et al., 1999). The aim of this paper is to classify and to provide a first step in a comprehensive study on the potential use of green façades to improve the local air quality in urban environments.

In the presented research, adsorption and removal of particulate matter by vegetation are discussed because of the associated increased morbidity and mortality aspects of inhalation fine atmospheric particles by humans. Especially finer particles (those with an aerodynamic diameter of <10 µm (PM_{10}), pose a long-term threat to the human health, mainly to the human respiratory functions (Pekkanen et al., 2000). In general, the smaller the particles, the deeper they penetrate into the respiratory system were it is taken up into the blood. In this way, respiratory and/or cardiovascular disease arise (Pekkanen et al., 2000). Research done by Pope et al (2009) in the United States on the life expectancy of humans and the concentration of fine particulate air pollution, shows that there is an increase in life expectancy when there is a decrease of 10 µg per cubic meter in the concentration of fine particles in the ambient air.

Airborne particles are classified in fractions according to their size. The fractions are expressed in µm and refer to the maximum aerodynamic diameter of a spherical particle. The usual monitored size fraction is called PM_{10} (particles with an aerodynamic diameter smaller than 10 µm). Below PM_{10} the range of particle sizes found in the atmosphere is usually considered in three groups (EPA.gov; Bloemen et al., 1998; NEGTAP, 2001) namely:

1. Coarse particles: are larger than 2.5 µm and smaller than 10 µm in diameter and are mostly found near roadways and dusty industries.
2. Fine particles: are smaller than 2.5 µm and larger than 0.1 µm in diameter. This group is mainly found in smoke, car exhaust ad for example industries.
3. Ultrafine particles: are all particles smaller than 0.1 µm in diameter.

Literature review shows the importance of altering the amount of fine particles in the air to improve human health. Although this information, less research has been done on the potential impact of lowering the amount of fine particles by vertical greened surfaces and on counting the amount of adsorbed fine particles by leaves.

Past research methods focussed on particle mass levels through examine the effluent of washing urban tree leaves (Bartfelder and Köhler, 1987; Thönnessen, 2000; Beckett et al., 2000; Freer-Smith et al., 2005; Maher et al., 2008). In assessing the potential benefit of fine particle adsorption by green façades this paper examines if there is an influence of rainfall simulation on particle retention by vegetation. Besides that the paper intended to classify the amount of particles by a counting method based on Environmental Scanning Electron Microscope (ESEM) images. The method of using micrographic images in combination with an image analyzer (*Image J*) enables to study and identify particle size, origin and amount directly on leaves.
The surfaces of vegetation are recognized as a terrestrial sink for atmospheric particulate matter, consisting of particles which are highly variable with respect to origin, chemical and physical properties, elemental composition, and potential biological and environmental impact. Vertical greened surfaces may be especially efficient filters of airborne particles (Powe et al., 2004) because of their high surface to volume ratio of foliage, abundant petioles and twigs, and due to hairy, wax structure or rough leaf surfaces and shapes. To estimate the filtering effects of façade greening, it is necessary to study the relationships between the retention of particles on the leaf surfaces and the local pollutant concentration. Also the resuspension of already adsorbed particles is an important parameter in the purification process. Processes which have to be taken into account for resuspension of particles are among other things: wind, rainfall and falling of leaves (figure 4.4.1).

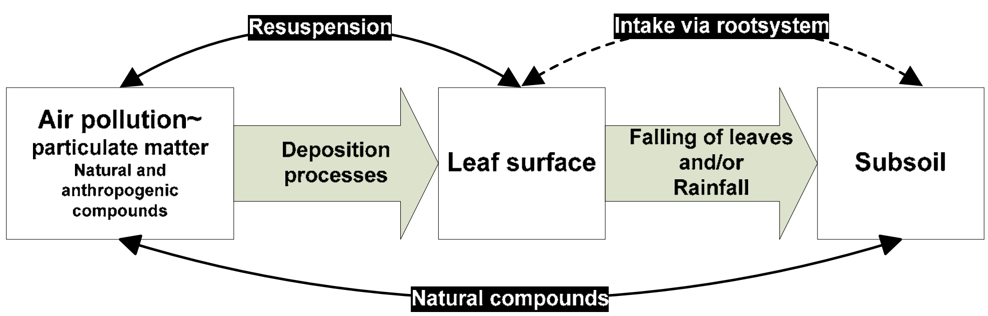

Figure 4.4.1 Conceptual model; relations between particles and leaves.

A literature survey done by the authors on the different mechanisms between particles and leaves shows that resuspension of particles is common stated but hardly investigated. Once fine particles are adsorbed by the leaf surface it is important to know if they still form a danger for human health as earlier discussed. Two main forces act on small, moving airborne particles: one is the force of gravity and the other is the viscous force exerted by the air through which the particles are moving (McCartney et al., 1982). If the particles are electrically charged they will also be subject to electrostatic forces, which may alter the dispersal and deposition patterns of charged particles compared with uncharged ones (McCartney et al., 1982). Some particles may be adsorbed into the tree but most are retained on the plant surface (Powe et al., 2004). Once particles are adsorbed to the leaf surface it is important to know the pathway that will bring these particles to the subsoil. Also the particle sizes involved in this process are of interested.

In this paper a simulated rainfall experiment was carried out on *Hedera helix* leaves (common ivy) to get more insight into the percentage of (fine) particles that can be washed off or that will remain on the leave surface with the potential to end up (resuspended) in the air again. According to Nowak (1994) the resuspension of particles can be up to 50% of the adsorbed particles.
The objective of this study aimed in defining the reduction of air pollution and stimulating the ecological performance of vertical green (green façades, sound barriers, etc.) with plants. The interaction or filtering effect between (vertical used) vegetation and air pollution (particulate matter) is not well studied yet. Especially the effect of rainfall on particle retention and resuspension is unclear. The approach in this research is not to measure the mass of particles collected on the leaves but the amount of adsorbed particles. Measuring the mass of particles instead of the size and amount of particles ignores the risk for human health with respect to hearth and lung diseases. Since particle size is correlated with lung diseases (it is important to know how many of those fine or ultra fine particles are adhered on the leaf surface. Counting particles on a specific leaf area seems therefore more suitable for this experiment.

Materials and methods

Leaves of common ivy (*Hedera Helix*) were chosen for this experiment. The leaves were collected from a vertical greened fence near Steenbergen (The Netherlands) in the beginning of October 2008, after a period of 6 days without rain. Eleven adult ivy leaves and only entire green leaves were taken randomly from the outside ivy foliage of the greened fence. The collected leaves were sealed and labelled separately in plastic containers to exclude the possibility of contamination after sampling. The sealing procedure was done in a way to keep the leaf surface untouched until the examination in the Microlab of Delft University of Technology.
To distinguish the difference between the amount of particulate matter before and after rainfall on the leaves (only the upper side of the leaf is examined in this research), micrographs where taken with an Environmental Scanning Electron Microscope (Philips XL30 ESEM with a tungsten filament) at different magnifications namely 100x, 500x and 5000x. An experimental procure was addressed in order to make micrographs before and after rainfall simulation on the same leaf and on the same spot, valid for each magnification. The micrographs are always taken in the middle of the leaf left-handed near the central nerve (figure 2 right). When a spot is found, the spot is fixed in the middle of the view and the

micrographs are taken at different magnifications. After this session the leaf is exposed to a simulated rainfall.
Therefore the leaves were placed in a tripod on a bench in which all rainfall events were performed. Rainfall was simulated with a pressurized system utilizing a rain nozzle designed to project a downward spray. The nozzle was placed about 60 cm above the leave(s) and a uniform spray was attained to simulate the rainfall. The leaves were subjected to a simulated rainfall event of 15 minutes at a rainfall rate of 80 mmh^{-1} with normal tap water (pH 8.0) measured with a funnel with a diameter of 13 cm. A relative high rainfall rate was chosen for this experiment to make sure that the leaf was fully wetted.
After the simulated rainfall event, the leaf was placed again in the ESEM chamber with the positioning holder (figure 4.4.2 left). Micrographs were taken at the same spot as before the rain simulation. This procedure was repeated for each of the collected leaves. In this system the computer is responsible for beam control, image analysis, data processing and data storage. For image analysis, the backscattered electron signal is used to create a binary image of the leaf surface with the adhered particles.

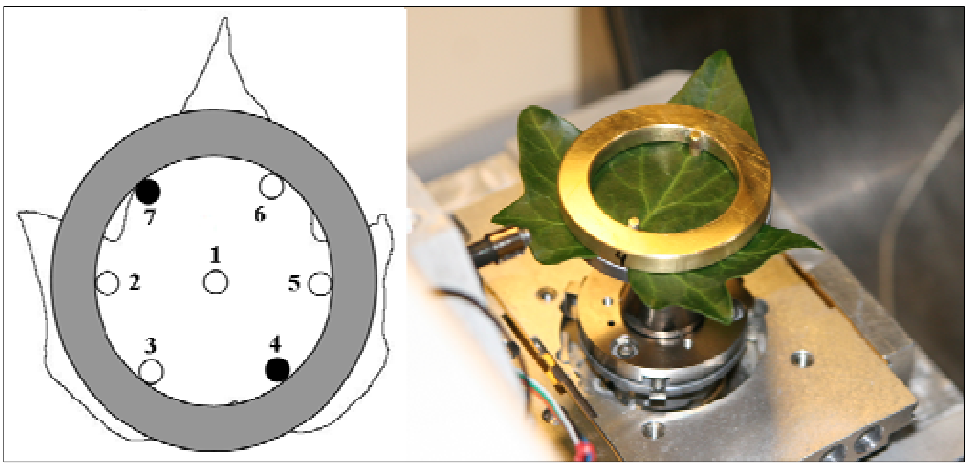

Figure 4.4.2 Sampling procedure using ESEM analysis.

After collecting microphotographs the particle counting was done automatically with an image analyzer software package called *Image J*. Particle analysis requires that the image is a "binary" image (i.e. black or white). The biggest issue is to distinguish the particles from the background (threshold). See figure 4.4.3 and figure 4.4.4 to go from raw to threshold. The automatic threshold function used by *ImageJ* was applied, in some cases manual correction of the automatic threshold value was needed. Further information about the program can be found on http://rsbweb.nih.gov/ij/.
Particles that are slightly overlapping in a threshold image must be separated; this was done with the watershed function in *Image J*. Once the particles have been successfully threshold and watershed, they can be analyzed to obtain information regarding particle size and numbers. In the analysis no boundary to the circularity

value was given (i.e. a value of 1.0 indicates a perfect circle), which means that all various shapes of particles were count.

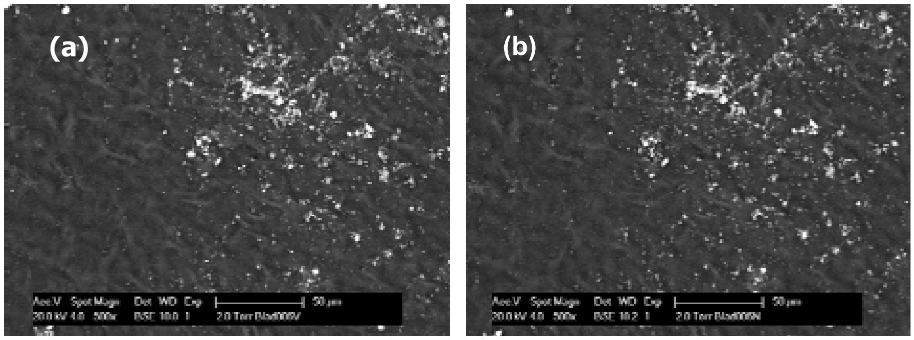

Figure 4.4.3(a) ESEM micrograph before rainfall, (b) ESEM micrograph after rainfall.

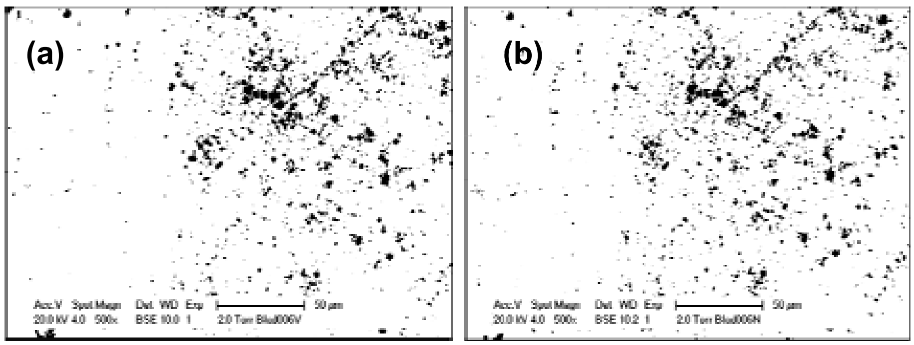

Figure 4.4.4(a) Threshold micrograph before rainfall, (b) Threshold micrograph after rainfall.

Per magnification (100x, 500x, respectively 2500x) the different adsorbed particles were count, also weight factors, respectively 1, 25 and 2500 times, were used to compensate for the loss of counting area (zoom effect). In addition, the cross sectional diameters of each of the particles were calculated by assuming that a calculated area belongs to a certain aerodynamic diameter. The experiment and procedure for counting was repeated and carried out for each individual examined leaf.

The presented counting procedure was done by second year's students from the Faculty of Civil Engineering of Delft University of Technology and the students are instructed how to analyze the micrographs. Each leaf was measured by a new group of students, a group exists out of six students and each individual student in a group analyzes the same photo series before and after simulated rainfall. The groups of students were used to examine if there is an influence on the sensitivity of the used image analyzing procedure. The total of used specimens (different leaves) and thus also the number of groups for this experiment was eleven (each leaf is thus counted by six different persons).

The collected data (response variable) from the counting procedure was evaluated by an replicated random block design (ANOVA) to test an eventual influence of the students (independent variable) on the counting procedure and the effect of simulated rainfall (independent variable) on particle loss Each collected data set was filtered (the six outcomes of the counting procedure for each leaf before and after rainfall) by testing for outliers. This filtering procedure was done on the basis of Chauvenet's criteria assuming that each individual data set follows the normal distribution. The rejected outliers were considered as a "malfunctioning" of the students. The statistical analysis was performed by SPSS 16.0 software package. The level of significance used in the analysis and throughout the paper is alpha 5%.

The outcome of this analysis will give more insight into the relevance and interactions between the retention of particles on leaf surfaces and the influence of rainfall on the retention. Also the sensitivity of the counting procedure (with relation to the need of qualified personnel) can be examined. The statistical outcome enables also $H_{\emptyset}$ hypothesis checking.
In this study, we hypothesized that rain changes the amount of adsorbed particulate matter on ivy leaves and that students will not have an effect on the outcome of counting particles.

Results

Outcome of counting particles before and after simulated rainfall

The result of counting particles on a specific leaf area (950x1275 μm^2) results in a particle distribution (figure 4.4.5) for the upper side of the leaf. Particle sizes ≥ 10 µm appeared to be rather rare compared to particles sizes ≤ 10 µm. Particles larger than 10 µm will thus not be studied in this paper. Almost all of the peaks were found in the range up to 2.5 µm. The smallest particles that are found with the applied measurement technique are in the range of 0.2 µm. Rainfall did not have a significant effect on the number of particles retained on the leaves. The number of particles (table 4.4.1) before the rainfall ranged from ± 29000 to ± 199000 particles per μm^2 and was not significantly different from the number of particles (respectively ± 21000 and 160000 particles per μm^2) retained on the leaves after the simulated rainfall event (figure 4.4.5). For leaf 5 and 11 a negative value was found for the amount of particles after the measurement. This means more particles entered the counting area after the simulated rainfall event.

Table 4.4.1 Outcome of counting fine particles based on ESEM images; before and after simulated rainfall.

Blocks	Treatment		
(n=11)	***before rain*** *(x)* *average out of six students (n=6)*	***after rain*** *(y)* *average out of six students (n=6)*	***difference*** *(x-y)*
leaf 1	96952	81396	15556
leaf 2	78277	64609	13668
leaf 3	34648	27410	7238
leaf 4	33376	28296	5080
leaf 5	86644	87235	-591
leaf 6	130134	51011	79123
leaf 7	29285	21016	8269
leaf 8	75499	52146	23353
leaf 9	199813	160142	39670
leaf 10	185010	164838	20172
leaf 11	48413	144531	-96118

Evaluation of statistical analysis

Throughout this paper differences between samples are indicated to be significant if they were significant at $\alpha < 0.05$ based on the results of the paired t-test (table 4.4.2). The F-test is done on each individual counting procedure. The outcome of the statistical analysis identified that in the presented study no significant differences were found between the treatments. The null hypothesis that rain may not have an effect (P=0.186) is thus rejected. However the hypothesis that students (P=0.000) will not influence the outcome of particle counting is accepted.

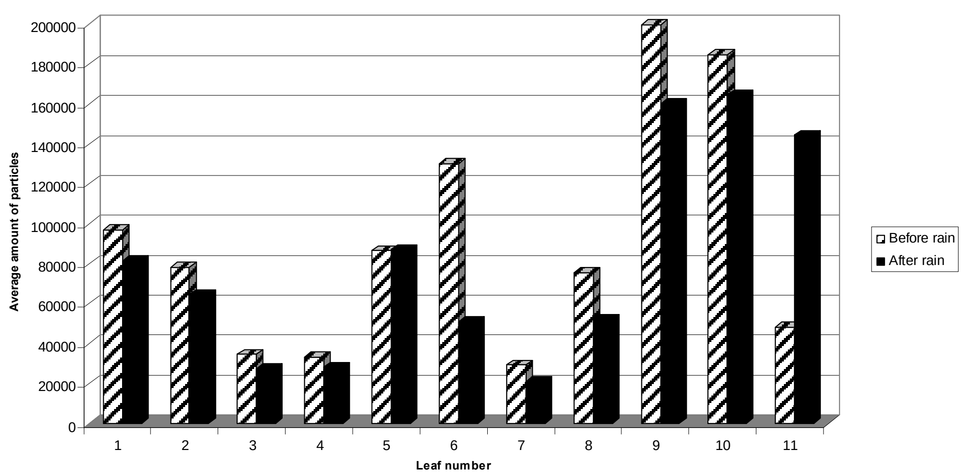

Figure 4.4.5 Average amount of particles found on Hedera helix leaves before and after simulated rainfall.

Discussion

In this paper the effect of rain on the cleaning effect of leaves has been studied. Eventual cleaning effect of leaves by rain will lower the chance that particles will be affected by wind loads (resuspension). Rainfall may influence thus (in) directly the capacity and efficiency of the leaf on particle reduction in the ambient air. Simulated rainfall shows that the expectations with respect to particle wash off and the self cleaning effect of *Hedera helix* leaves are far away from ideal.

For leaf 5 and 11 consequently we found more particles in the counting area after the simulated rainfall. This means that particles are moved from the area around the examined spot into the counting area. With other words particles are not always fixed on the leaf surface which can be explained by figure 4.4.6, were we see an accumulation of particles especially near the edge or tip of the leaf. The photograph also suggests that there is a particle transfer over the leaf surface. The overall result however of the experiment shows that the simulated rainfall has a minor effect on the self cleaning effect of *Hedera helix* leaves on particulate matter.

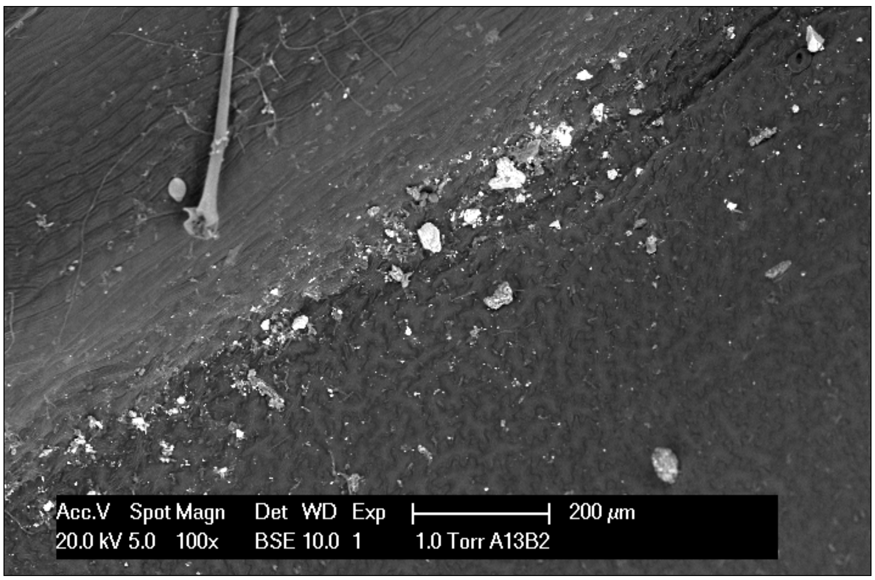

Figure 4.4.6 Accumulation and clogging of particulate matter on the edge of a leaf.

This leads us to the next question whether particles retained on the leaf surface after the rainfall have the potential to end up (resuspended) into the air again due to wind turbulences. The question that can be raised concerning the outcome of this experiment is how likely this resuspension of particles is after a rainfall? Additional wind experiments concerning particle loss are necessary to detect the effect of air turbulence in regard to this statement. Most of the particles are still present on the leaf surface after the heavy simulated rainfall, so the particles are really well embedded on the leaf surface. Is there an explanation for the minor particle loss due to the effect of rainfall and that the particles are well embedded?

Is there a role for the leave composition (wax layer, hairy, rough surface, etc.), the leaf boundary layer or electrostatic behaviour of particles and leaf surface?

The wax layer can be of importance to stick the particles, but is most unlikely to be able to hold on after the rain experiment of a simulated rainfall event of 15 minutes at a rainfall rate of 80 mmh^{-1} with normal tap water (pH 8.0). Wax structures consist of saturated very-long-chain fatty acids (commonly C_{20} to C_{34}) and in surface structure not equipped to hold fine dust particles (Samuels et al., 2008, Koch & Ensikat, 2008 and Niemietz, 2007). A well understood surface wax structure of the Lotus, *Nelumbo nucifera*, is even been used for its properties of self cleaning effect, due to the laminar special wax structure (Müller et al., 2007). This also explains the observed lacking of large fine dust particles of 10 µm or more on the leaf surface at all. Besides the difficulty of fixation, all large particles of 10 µm or more are washed away at a high relative humidity together with low temperatures, which could easily form a dew point effect on the leaf surface, or in cases of precipitation, or in situations of a dry environment due to wind turbulence.

The hairs are lacking on common ivy, so this factor is of no importance concerning the fine dust particle adhesion. The leaf boundary layer is extremely related to the wax structure of the surface of the epidermal cells. As mentioned before, the leaf boundary layer and the fixation of fine dust particles of 10 µm or more can been seen in the same way as the given structural analysis of wax surfaces. In conclusion, it is very difficult to hold these large fine dust particles of 10 µm or more on the leaf surface of common ivy based on the leaf composition (wax layer, hairy, rough surface, etc.) or on the leaf boundary layer.

If a boundary layer could be part of the adhesion factor after the mentioned rainfall, then it can only remain the adhesion properties of fine dust particles when there is a strong bonding of fixation. The only possible strong bonding on the molecular level which resists the test of a 15 minutes rainfall with a rate of 80 mmh^{-1} will be a Van der Waals bonding. A Van der Waals bonding can only be induced due to a transition of another extra energy source, like an electrical charged fine dust particle.

The main sources of fine dust particles of 10 µm or more are known from sand-, clay- or biological origin. In cases of smaller distributions, particles of less than 10 µm, the main origin is from gas exhaust of combustion and engines. The result of the findings in this research on common ivy shows clearly a dominant persistence of particulate matter smaller then 10 µm in diameter. The samples of common ivy mentioned in this research are all exposed to the influence of traffic.

Fine dust particles of combustion and engines consistently exhibits in the soot mode of 20 till 200 nm size with a substantial fraction of 40 till 60 percent of charged particles (Maricq, 2010). This means that more then half of all fine dust particles of combustion or engine origin are charged and these particles will be neutralized as soon as it touches the leaf surface. The common ivy is connected with its root system to the soil, so per definition charged in the same manner as the soil it self or in other words the electrical charge can be seen as grounded (Becquerel, 1847 and 1875).

In short, the particulate matter either gains electrons in cases of positive charged fine dust particles or lose electrons in cases of negative charged fine dust particles. Because no electrical charged energy can get away in any other form, as soon as a fine dust particle touches the leaf surface of the common ivy, the electrical charge will be converted into a strong Van der Waals bonding. A Van der Waals bonding is known in physics to be an extreme strong fixation bonding, so this explains and underlines the positioned particulate matter on the leaves of common ivy after the 15 minutes at a rainfall rate of 80 mmh^{-1}.

Conclusions

Since the research was focused on the effect of rainfall on particle retention on the leaves of common ivy (*Hedera helix)* we can conclude that the cleaning effect of rainfall for the fine and ultra fine particles is very low. However, the observed phenomenon of the remaining of the particulate matter on the leaf surface brought us to basis principle of physics of a Van der Waals bonding as the only possible explanation of fixating after 15 minutes at a rainfall rate of 80 mmh^{-1}. The electrical charged particles of gas exhaust of a combustion or engine source can be considered as the most important factor of the remaining of the particulate matter of less than 10 μm on the leaf surface of common ivy of our research. The fine dust particles of 10 μm or more have not been observed in this study on the leaf surface of all sampled common ivy. The adhesion of these relative large fine dust particles is possible washed or blown away as mentioned and discussed in this article.

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The Microlab of Delft University of Technology, Faculty of Civil Engineering and Geosciences is acknowledged for the permission to make use of the necessary research facilities. The authors would also like to thank the second year students of the year 2008 for collecting the data (analyzing micrographs) needed for this experiment. We also thank Mr. A. Thijssen for his technical support, making the ESEM micrographs and data processing.

4.5 Comparing ivy (*Hedera helix*) leaves with different materials on PM_x adsorption capacity, using an ESEM based counting method

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M. Ottelé[1], M.A. Mir[1], T. Guiberti[2], A.L.A Fraaij[1], H.D. van Bohemen[1]
[1]Faculty of Civil Engineering and Geosciences, Delft University of Technology
Stevinweg 1, 2628 CN Delft, P.O. Box 5048, The Netherlands.
[2]Department of Civil Engineering, Ecole Normale Supérieure de Cachan

Abstract
This paper contains an experiment, in which ivy (*Hedera helix,* evergreen specie) leaves PM_x absorption capacity is compared with other materials. The experiment is carried out in three different locations with materials such as glass, aluminium, painted metal and high quality paper. The samples are installed on two panels (wooden support) and placed outdoor for twenty days. Beside the panel with the samples, also ivy was placed in the near vicinity of the panels. The locations were in the Microlab of Faculty of Civil Engineering of Delft University of Technology, nearby the highway A13 and in the Botanical garden of Delft University of Technology. The experiment took place in the autumn and after twenty days of exposure the particles were counted via ESEM micrographs and *Image J* processing software.
The aim of this paper is to compare results on PM_x absorption capacity of ivy plants leaves with other building façade materials. The outcome of the experiment shows that the A13 (highway The Hague- Rotterdam) is the most polluted site and that particles are mostly absorbed under 3 µm. Then concerning materials comparison, painted metal has a high absorbing capacity followed by leaves, aluminium, paper and glass.

Keywords: vertical green, green walls, particulate matter (PM_x), *Hedera helix*, ESEM micrographs.

Introduction
Green has mainly better effect in time of stress in our life (Krusche et al., 1982; van den Berg et al., 2010). But unfortunately because of increasing urbanization in the last time, a lot of people become more and more displaced from green areas (van den Berg et al., 2010). Green space in the living environment can be an important environmental factor, which can have influence on our health (van den Berg et al., 2010). Green can be applied in living environments in different ways. Greening of façades or in short 'Vertical green' is one of the applications of green. A view back in history shows that green façades are already existing from the past (Köhler, 2008). People have always tried, to give a beautiful image to the façades and other structures with applying green on it. The simplest way to apply vertical green is to plant ivy plants, which have an adhesive character on the façades.

Nowadays green façades can be applied as a new technology and also offers many benefits as a component of our current urban design (Köhler, 2008). Aesthetics, energy saving and air quality improvement are the major benefits of green that can be mentioned (BioScience, 2007). Beside the mentioned benefits, green façades have also another benefit namely the absorption of fine dust (Particulate Matter) from the air.
At present there are many problems with particulate matter (PM_x), due to exceeding of the concentration limits given in the standards (EPA.gov). The penetration of PM_x 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).
Particulate Matter (PM_x) is a fine substance in air pollution, which in too high concentrations can be found in some places. PM_x in the air varies strongly in size, in chemical composition and in concentration. The size of particles is directly linked to their potential for causing health problems (Pope et al., 2009). Scientists are concerned about particles that are 10 μm in diameter or smaller because those are the particles that generally pass through the throat and nose and enter the lungs. Once inhaled, these particles can affect the heart and lungs and cause serious health effects as cardiovascular issues (Pekkanen et al., 2000; Pope et al, 2009). Particle pollution is grouped into three categories (EPA.gov).

- Coarse particles: such as those found near roadways and dusty industries, are larger than 2.5 μm and smaller than 10 μm in diameter.
- Fine particles: such as those found in smoke and haze, are 2.5 μm in diameter and smaller. These particles can be directly emitted from sources such as forest fires, or they can be formed when gases (emitted from power plants, industries and automobiles) react in the atmosphere.
- Ultrafine particles: such as combustion processes, are 0.1 μm and smaller.

Because of public health it is important to develop ways in order to reduce PM_x concentrations in inhabited areas. Greening our urban environment with vertical green and green roofs can fulfil this requirement, for this reason it is necessary to understand the relation between particles and vegetation better.

Experimental description
This experiment quantifies the PM_{10} absorption by different building materials (aluminium, glass and painted metal) and compares that with *Hedera helix* leaves. Actually, to justify the use of green walls for its depolluting function, it is important to know if plants have a stronger adsorption capacity in comparison to usual building materials like glass, aluminium, or paint. Just by scientific curiosity, it is interesting to test less common materials, such as high quality paper for example for quick shelters after a calamity. The materials will be tested outdoor during twenty days to catch particles. Also the experiment will be settled in two different test sites with different environments to investigate the difference in particle

adsorption. The samples of the materials will be installed in a green environment surrounded by middle density roads (Botanical garden of Delft University of Technology) and nearby a high density highway (A13). The materials are installed on wooden structures (panels) which are shown in figure 4.5.1. After a short study of ivy leaves orientation, 30° seems to be a good average angle with the vertical, for this reason all the material samples were installed with a 30° angle.

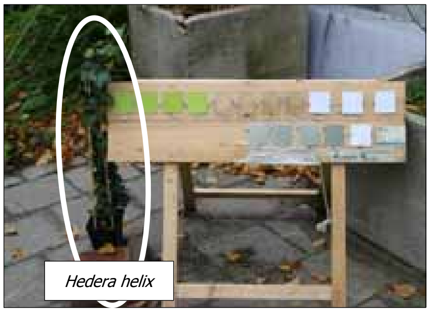


Figure 4.5.1 Left; Location botanical garden TUDelft; Right Location next to highway A13.

It is also necessary to know the initial profile of the particles population in the samples to compare in-situ absorption levels. Therefore the results of experiment which was installed in the laboratory (Microlab of Faculty of Civil Engineering) will be used to compare the absorption capacity of the materials as a kind of reference. That experiment is carried out with the same purpose and in the same way as for the other two locations.
The maximum level for the particles in the air is 40 µg of PM_{10} in a m^3 air and given in the standard (MNP, 2008), but it can not give any information about the number of particles. A high concentration of particles can be due to a heavy metal particle when a low concentration of numerous ultrafine particles can be more dangerous. The degree of hazard is not linked to the mass but to the number and the size of the particles. Therefore, this experiment will focus on the amount of particles and not to the mass.
To count the number of particles, an electron microscope ESEM (Philips XL30 ESEM with a tungsten filament), will be used to make micrographs in three different magnifications, respectively: 100x, 500x and 5000x. After that, the micrographs will be studied with specialized software *Image J,* which counts the amount of particles on the micrographs and in certain particle classes.

Climbing plant and the Materials
Hedera helix (or common ivy) is a very common variety for a green cover on natural or artificial vertical surfaces. *Hedera helix* is applied from the past as evergreen species on buildings and other structures. For this reason, it seems to be a relevant choice concerning the development of green façades and to use this species for comparison with other materials. The first material is aluminium. Aluminium can be applied as a façade material in different ways. It will be tested as an aluminium plate without any coating. The second material used is glass. All buildings have windows and nowadays the architects try to design lots of buildings with large glass surfaces. Moreover, the low roughness of window glass totally

differs from other materials. The third material is high quality paper. Because of an outdoor situation and possibilities for rainfall, a high quality paper (200 g/m^2) is used. The fourth material is painted aluminium as a simulation of the skin of numerous industrial buildings.

Test sites (locations)
To test the materials for the adsorption capacity of particles, it is necessary to know the initial amount (reference) of particles on each material surface. A controlled storage, located in the MicroLab of the faculty of Civil engineering was used to ensure that the used samples will not absorb particles and to make it possible to compare the materials before and after twenty days of outdoor exposure. The Botanical Garden of Delft University of Technology has been used for exposure the samples in a green space, surrounded with middle density roads. It is also a safe place for the installation of the test set-up, because of the good protection against vandalism. The third site is close to the A13 (a very high density highway in the Netherlands). The wooden structure of the panel is painted green, to hide it against vandalism. For this reason the panel is placed between shrubs close to the road, see also figure 4.5.2, the locations of the test sites.

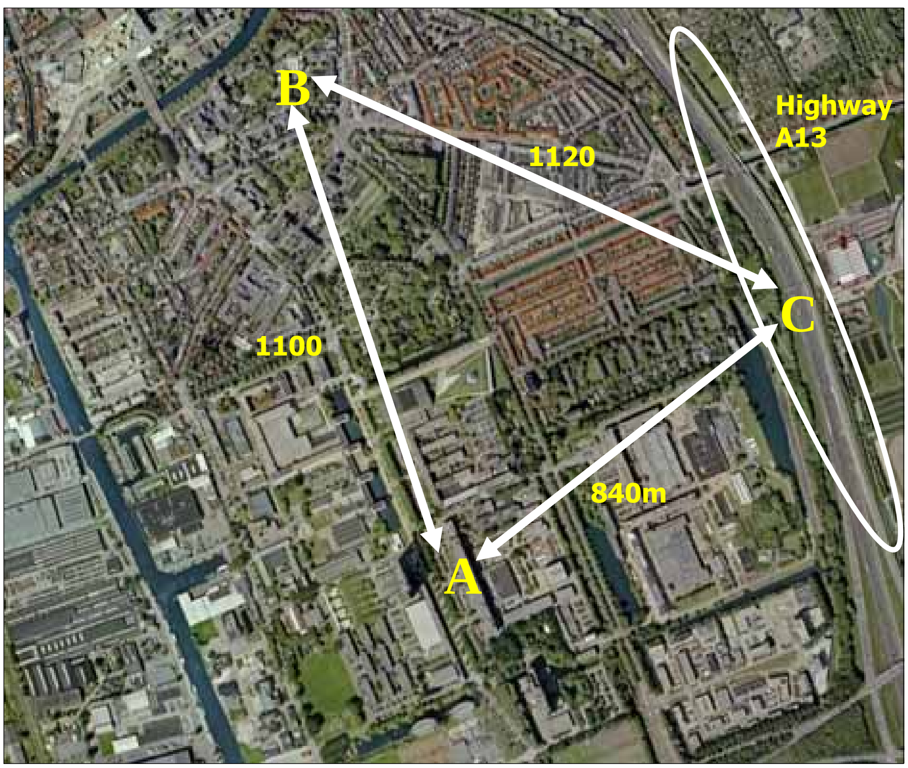


Figure 4.5.2 Location of the three test sites, A (Microlab), B (Botanical garden) and C (Highway A13).

Counting particles, using ESEM (Environmental Scanning Electron Microscope)

An ESEM (Philips XL30 ESEM with a tungsten filament) is used to count the number of particles on each sample. The used electron microscope, cannot handle samples larger than 10x10 cm^2. For this reason, the sizes of the samples were chosen to have a surface of 5x5 cm^2. Three magnifications (100x, 500x and 5000x) are used to make micrographs of each sample. For a good focusing of each sample, it is important to start on a high magnification (5000x) and to zoom out for making micrographs on a lower magnification. After collecting of all the micrographs at different magnifications for all the samples, the particles visible on the micrographs can be counted automatically with *Image J* processing software. Figure 4.5.3 shows a leaf and the fixing ring in the ESEM chamber.

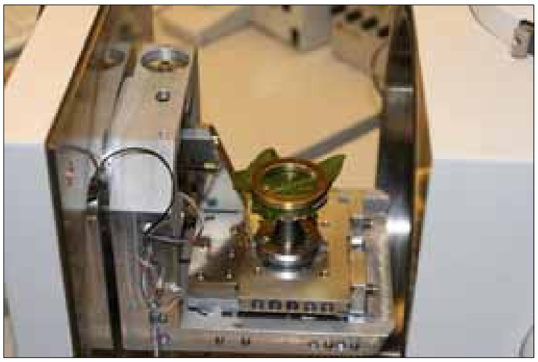


Figure 4.5.3 Hedera helix leaf in the ESEM chamber.

Particle analysis requires that the image is a "binary" image (i.e. black or white). The manual threshold function in *Image J* is used to distinguish the particles from the background. See figure 4.5.4 from raw to threshold. Further information about the program can be found on http://rsbweb.nih.gov/ij/. Particles which are slightly overlapping in a threshold image must be separated. Therefore the watershed function in *Image J* is used. Once the particles have been successfully threshold and watershed, they can be analyzed to obtain information regarding particle size and numbers.

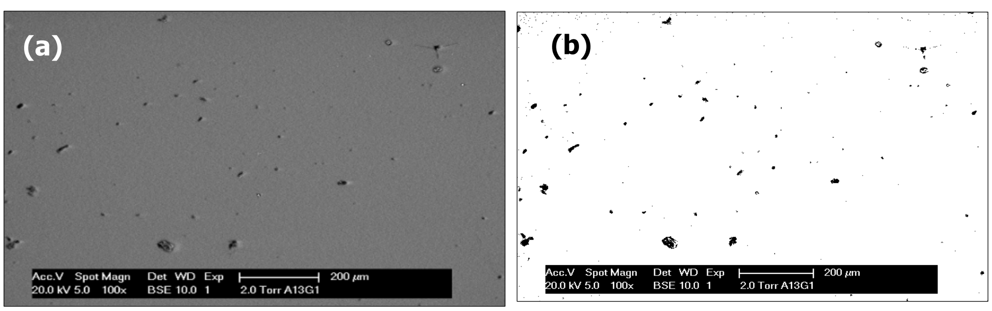


Figure 4.5.4 Micrograph of a glass sample before (a) and after (b) thresholding.

The adsorbed particles were counted per magnification. And also weight factors, respectively 25 and 2500 times, were used for the magnifications 500x and 5000x to compensate the loss of counting area (zoom effect). In addition, the cross sectional diameters of each particle was calculated, assuming that a calculated area belongs to a certain aerodynamic diameter. The experiment and procedure for counting was repeated and carried out for each sample.

Data organization

To ensure that a particle will not be counted double in the procedure, due to different magnifications on the same spot, the overlap of particle sizes per magnification was determined. The 5000x micrographs take only the particles smaller than 0.6 µm into account. The 500x micrographs count the particles between 0.6 µm and 5.50 µm, the 100x micrographs count only the particles larger than 5.50 µm. Moreover when the magnification is higher the examined area is lower. This is because of the zoom effect. For this reason zoom factors must be applied to take this effect into account. Particles from 500x micrographs are multiplied by 5x5=25 and particles from 5000x micrographs are multiplied by 50x50=2500.

The results are put together into two parts, first the particles distribution is debated for each material, and secondly the hierarchization of the material for its absorption capacity will be examined.

Results

Particle size distribution

Figures 4.5.5 shows the number of particles absorbed of each size for the five materials in the three locations.

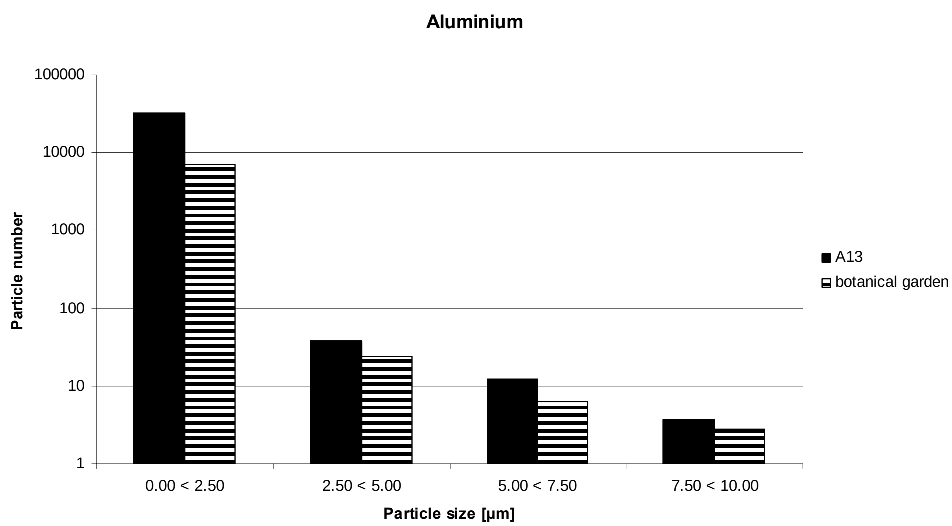
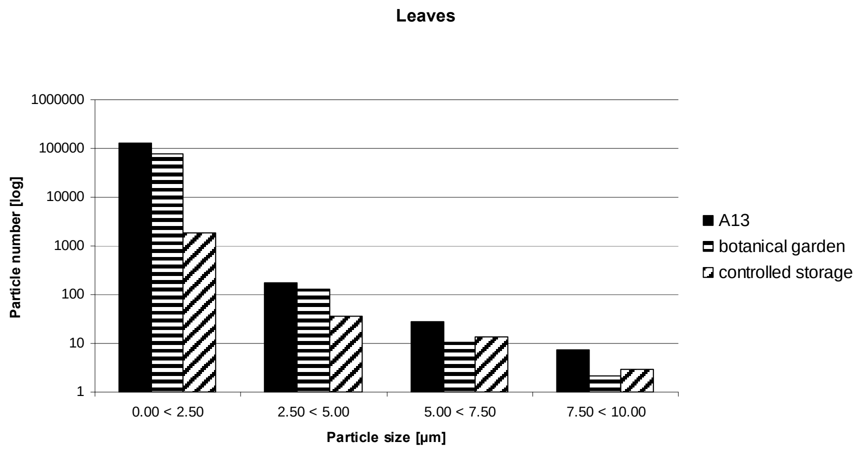
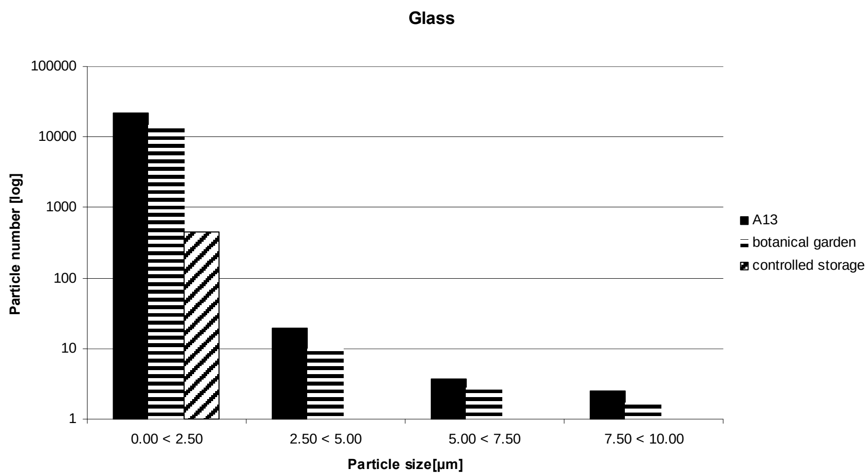
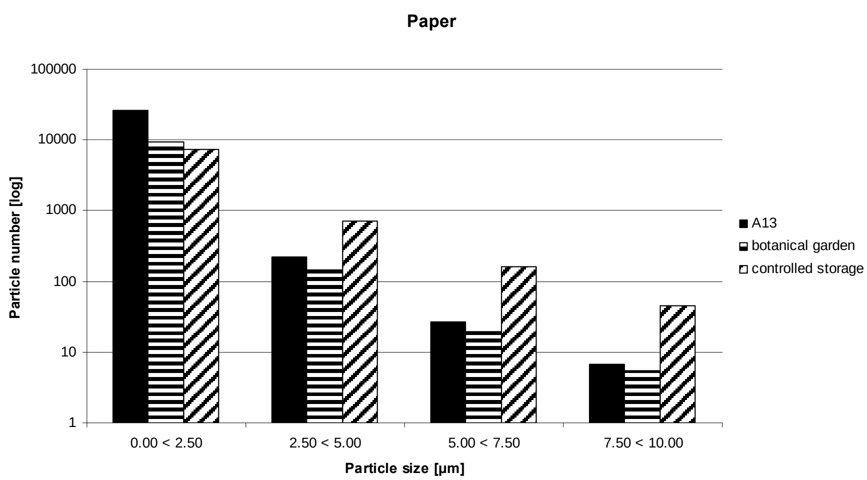
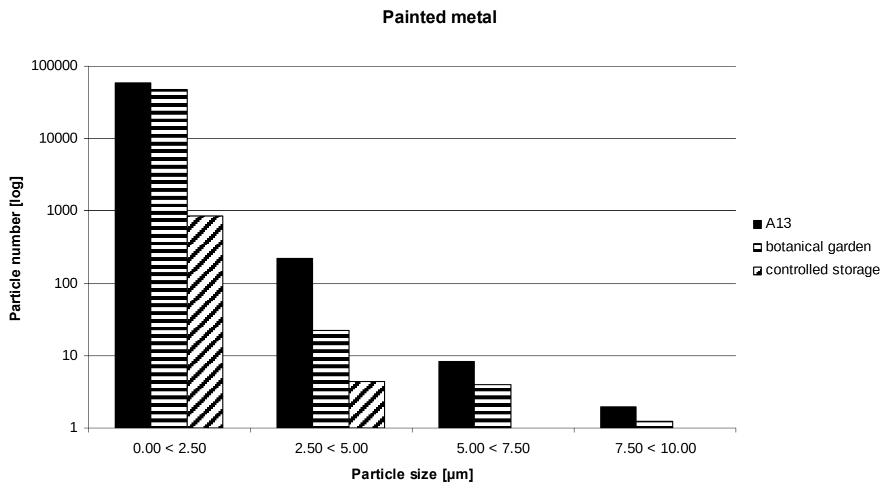


Figure 4.5.5 Particles absorbed on the three test sites for the five materials sorted by size.


Leaves
1000000
100000
10000
1000
100
10
1
Particle number [log]
0.00 < 2.50
2.50 < 5.00
5.00 < 7.50
7.50 < 10.00
Particle size [µm]
A13
botanical garden
controlled storage


Glass
100000
10000
1000
100
10
1
Particle number [log]
0.00 < 2.50
2.50 < 5.00
5.00 < 7.50
7.50 < 10.00
Particle size[µm]
A13
botanical garden
controlled storage


Paper
100000
10000
1000
100
10
1
Particle number [log]
0.00 < 2.50
2.50 < 5.00
5.00 < 7.50
7.50 < 10.00
Particle size [µm]
A13
botanical garden
controlled storage



The results could be split into two categories. In the first category, leaves, paper and aluminium have a full size range of particles adsorbed. The second category with the materials glass and painted metal has a particle size decrease after approximately 3-4 µm. This indicates that the air principally contains particles under 3 µm. It is important to notice that paper shows higher particle absorption than other materials. This might be due to the structure of paper. The structure can cause difficulties by thresholding process. The *Image J* processing software cannot make difference between some particles and the structure lines of paper (figure 4.5.6).

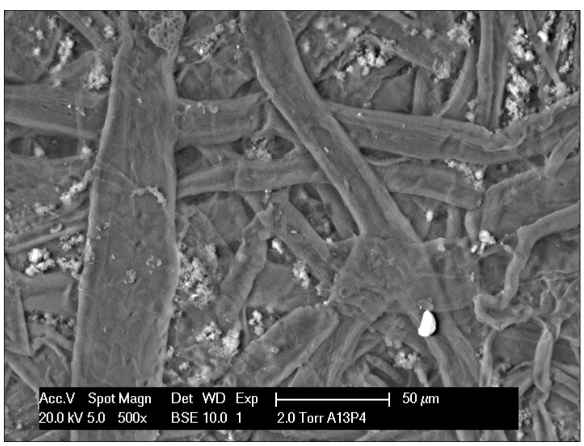


Figure 4.5.6 Paper sample in the ESEM.

Site impact and material hierarchization

Figure 4.5.7 shows the total number of particles absorbed by each material on the different test sites. Due to the test site characteristics one can expect high particles absorption in A13 and lower in the controlled storage. The following parts will explain material by material the potential reasons of such results.

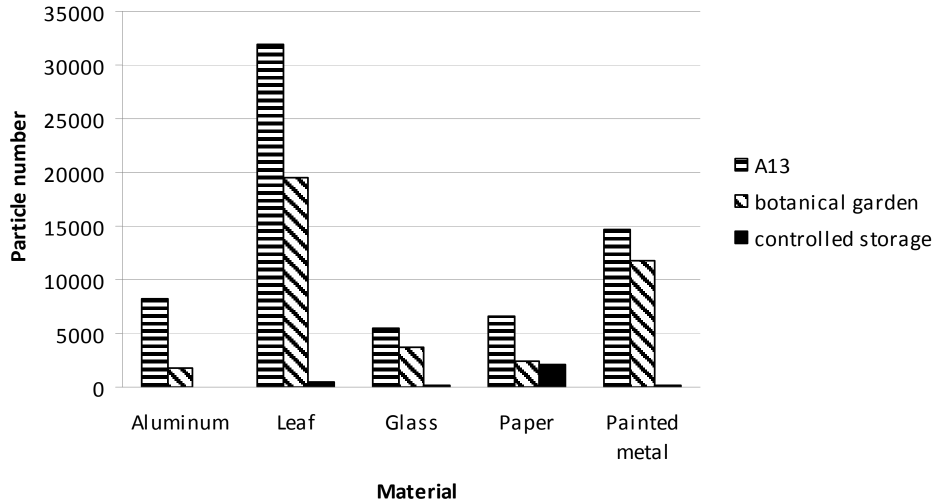


Figure 4.5.7 Total amount of particles absorbed by each material on each test site.

Aluminium

The amount of absorbed particles is clearly more at the A13 than in the Botanical Garden. However the texture of the aluminium surface can have an influence on the counting process. The software package *Image J* could not differentiate (thresholding) between particles and structures on the samples. Figure 4.5.8 shows two thresholded ESEM micrographs of aluminium samples on two different locations. As can be seen there are more particles nearby A13 than in the Botanical Garden.

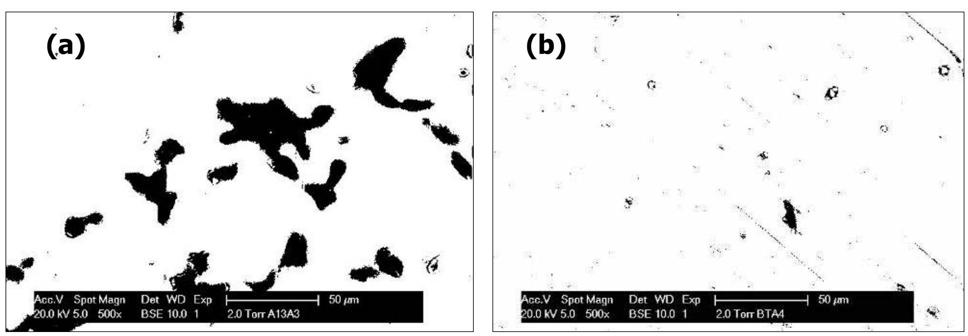


Figure 4.5.8 Particles on an aluminium sample, (a) A13 and (b) botanical garden.

Leaves

More particles have been absorbed at A13 than at the Botanical Garden, and the result of controlled storage is lower than the other two sites. The distribution of particles on the leaves near A13 and at the Botanical Garden is homogeneously. But the distribution of particles on the leaves placed in the controlled storage weren't homogeneous. In figure 4.5.9, it can be seen that particles are only present inside specific areas that seem to come from water droplets. Particles could have been stuck by water or nutrient spraying in the botanical shop before the plants were bought. This can explain the low amount of particles found on the leaves for controlled storage samples.

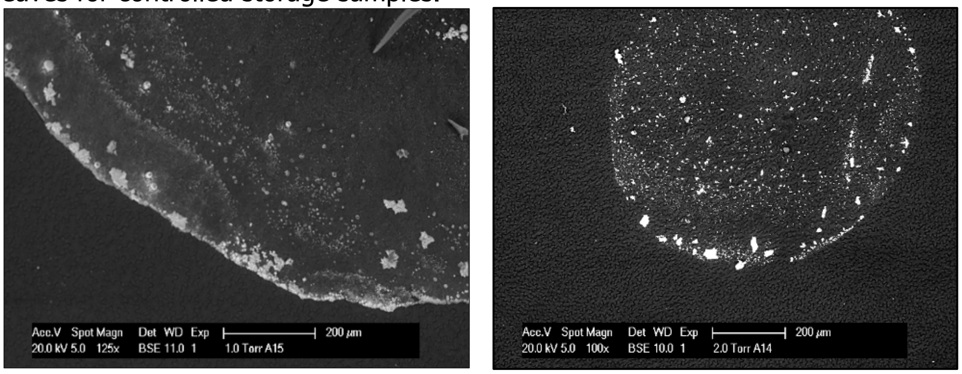


Figure 4.5.9 Two different leaves samples in the ESEM from controlled storage.

<u>Glass</u>

The glass behaviour is as expected, since the low number of absorbed particles derives from the high smoothness of the glass material. Figure 4.5.10 compares a glass 500x-photograph with a leaf 500x-photograph, on which the amount of particles is very clear. Also this material scores higher in particle adsorption close to the A13.

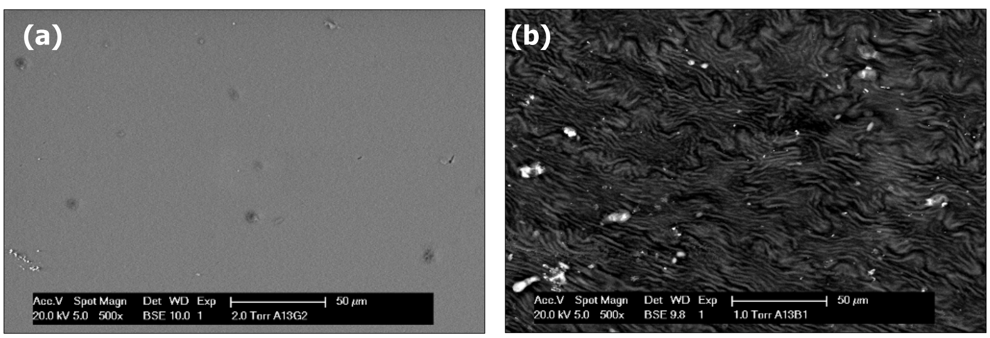


Figure 4.5.10 (a) glass sample from A13, (b) leaf sample from A13.

<u>Paper</u>

Also for this material the score of particle accumulation for the test site nearby A13 is the highest. This might be due to the high concentration of particles around the A13 (Figure 4.5.11). Paper can accumulate particles even if it is in storage. That means that paper can absorb particles during the time that paper can be naked on the top of the paper pile. Therefore a paper samples from the sheets between the pile of paper is used, and not the top one.

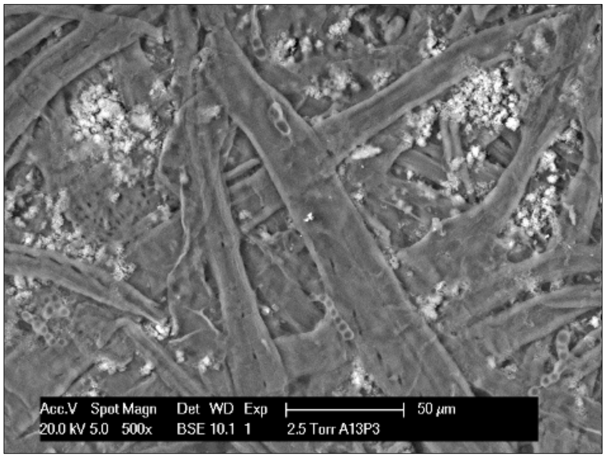


Figure 4.5.11 Paper sample with accumulated particles in the ESEM.

<u>Painted metal</u>

One can say that painted metal seems to have a high absorbing capacity. This is clear on the ESEM photographs. Figure 4.5.12 shows a 500x photograph of the metal sample. The roughness of the paint was high on a microscopic scale this is due to the pigment particles in the paint. The A13 samples absorbed more particles than the other locations. This is probably due to the higher concentration of particles around the A13.

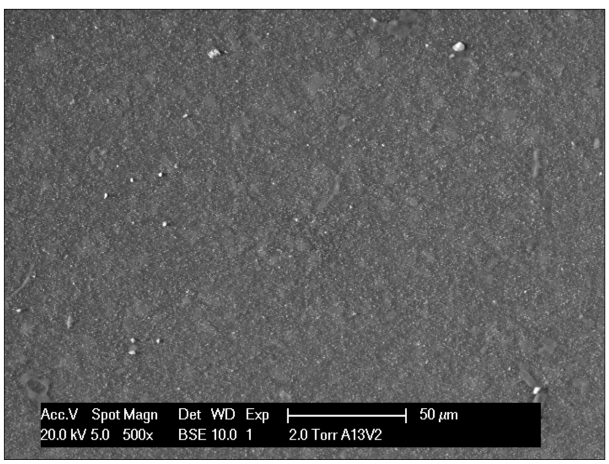


Figure 4.5.12 Painted metal sample in the ESEM.

Conclusions

The results show that the samples placed next to the A13 adsorbed more particles than the Botanical Garden. The largest amount of counted particles is found on the samples of leaves. Probably this is due to the high absorbing capacity of vegetation surfaces. As the results show, the glass surfaces are not efficient for PM_x absorption. This is might be due to the smoothness of the glass surface used in the experiment. Painted metal is also efficient in particle adsorption probably due to its

micro texture. Finally it seems that aluminium could not be so efficient for catching particles due to its texture surface. The *Image J* software was not able to differentiate between the texture and fine dust adsorbed on the paper samples.
In conclusion it can be mentioned that leaves absorb more particles than the other tested materials and that the samples placed next to the A13 were more polluted than the samples placed in the Botanical Garden and controlled storage.

Acknowledgments
The authors express their sincere thanks to Mr. Arjan Thijssen who helped with making the ESEM micrographs and to help with the data organization. The Microlab of the faculty of civil engineering and the Botanical garden of Delft University of Technology are acknowledged for their support.

4.6 Concrete as a multifunctional ecological building material: A new approach to green our environment

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M. Ottelè, D.A. Koleva, K. van Breugel, E.M. Haas, A.L.A. Fraaij and H.D. van Bohemen
Delft University of Technology, Faculty of Civil Engineering and Geosciences,
Stevinweg 1, 2628 CN Delft, P.O. Box 5048, The Netherlands.

Abstract
A lot of different green wall technologies already exist: one can think about systems with plants rooted in the ground or rooted in planter boxes. A new possible approach in greening façades and civil engineering applications is to use concrete surfaces as a medium for vegetation. With other words building materials that allows plant growth and comparable with wall vegetation. Wall vegetation stimulated on concrete structures and making use of the benefits of vegetation (for example: dust collection, temperature reduction, CO_2 reduction, and aesthetics) is a new multifunctional approach in sustainable building technologies. Combining new techniques such as green façades and cathodic protection allows to retrofit older constructions that have durability problems (reinforcement corrosion).

Keywords: *Concrete; Plants; Monitoring*;

Introduction
In this article the greening of concrete walls and façades is discussed, particularly the innovative use of concrete as a vegetation medium is highlighted. The novel research in the field of (wall) vegetation on concrete structures (i.e. building physics, sustainability and biological aspects) is presently taking place at Delft University of Technology, Faculty of Civil engineering, section "Materials and Environment".

Green roofs and green walls are good examples of integrating nature and buildings. The ecological engineering aspects of these examples are linking different functionalities to integrate the benefits for nature and humans (Bohemen, 2005). The main aims and benefits of these applications are:

- Energy saving by insulation (especially in the summer);
- Improvement of the microclimate (both indoor and outdoor);
- Adsorbing air pollution; the capability of plants to adsorb particulate matter (PM) and other air polluting substances;
- Aesthetical value;

- Green urbanized areas; façades with vegetation would provide plants and smaller animals with suitable habitats and therefore serve as important "steppingstones".

Façades, walls and for example sound barriers can form an ideal substrate for partial or full plant growth. Green façades offer the opportunity of having a perception of difference of the seasons. One can think about the design of new and existing structures and/or renovation projects, where a suitable solution for vertical green is possible. Different designs and implementation shapes are available for creating vertical green. The primary distinction between vertical greening systems are: rooted in the terrestrial soil or not directly rooted in soil (i.e. planter boxes, directly in some soil or foam integrated to the wall (Dunnett and Kingsbury, 2004; Köhler, 2008)). A more recent and sophisticated approach of greening façades is the use of wall vegetation. The main characteristics of the latter are that the plant is rooted in or on a building material (mostly stone or rock material). The nutrients and moisture is delivered from outside as well as by the building material itself. As a natural mechanism, wall vegetation is often found on older structures (quay-walls, bunkers, etc.) and typically requires a long-term (more than 30-50 years old) growing process (Darlington, 1981).

The possibility of growing plants on building materials, with the aim to allow mature vegetation within a relatively short period of time, provides designers, architects and building owners with a new innovative opportunity in the designing process. For example, concrete (as a building material) can form an excellent substrate for partial or full wall vegetation within a couple of years.

This paper discusses a completely new approach of integrating plant growth in building materials. Further, the application of green façades and protection techniques for reinforced concrete structures will be briefly discussed, aiming to show the more technical side of the "green façades" application, combining both durability and sustainability approaches in civil engineering.

Materials and methods

Green concrete (as a growing medium) is a material integrating concrete that offers structural strength with a base for vegetation, or allowing spontaneous colonization of wall vegetation in a very short time (expectation of growth is 1-2 years from the beginning of the building project). Concrete is known to be a porous material, for the hereby discussed applications, however, a special design is used: the concrete specimens have continuous air spaces in the top layer in which coarse aggregate (lava stone, fraction 32 mm) is hardened with the cement paste (Figure 4.6.1). The so-called porous concrete is filled with a special soil mixture and thus thinly covered with soil. Behind the porous layer, there is another layer of self compacting concrete, which forms the structural layer of the elements. The type of cement used for this experiment was blast furnace slag cement. The on-going experiment (started in the spring of 2009) comprises a total of 20 concrete prototype panels (each 500 x 500 mm high and 160 mm thick (80 mm porous layer and 80 mm structural layer)). The panels are planted with several plant species suitable for arid and high pH circumstances, and the development of the plants was monitored regularly. The plant species are as follows:

- *Thymus praecox*
- *Sedum (different species)*
- *Geranium cinereum subcaulescen*
- *Asplenium scolopendrium*
- *Asplenium trichomanes*
- *Cymbalaria muralis*
- *Aubrieta*

Figure 4.6.1 Green concrete prototype block created for plant growth.

Figure 4.6.2: The integration of plants and concrete.

As aforementioned, two layers form the concrete blocks, depicted in Figure 1. The A layer is a structural layer; it is a low porosity concrete able to bear heavy load. The B layer is the created growable layer. This layer has a high porosity, resulting from its' ingredients: lava stone with the fraction of 32 mm (lava stones are considered as light weighted granulates). Plants were further integrated in this very porous layer which was preliminary filled with a soil mixture. Figure 4.6.2 shows the result of plant growth on the concrete material after 7 weeks of installation.

Results and Discussion

The influence of concrete pH on the soil mixture inside the concrete blocks

Plants absorb soil minerals in ion form (NO_3^-, K^+,) to be able to grow (Darlington 1981). Plants need also specific minerals; the uptake of minerals is influenced by the pH change of the soil. As a consequence a plant survives in a specific pH range, most plants preferring the range of pH 6 to 8; some prefer more acid or basic environments. Therefore, it is important to have knowledge on the pH changes in concrete, being the medium for plant growth, in order to decide which plant species will be the most suitable option and will survive extreme circumstances.

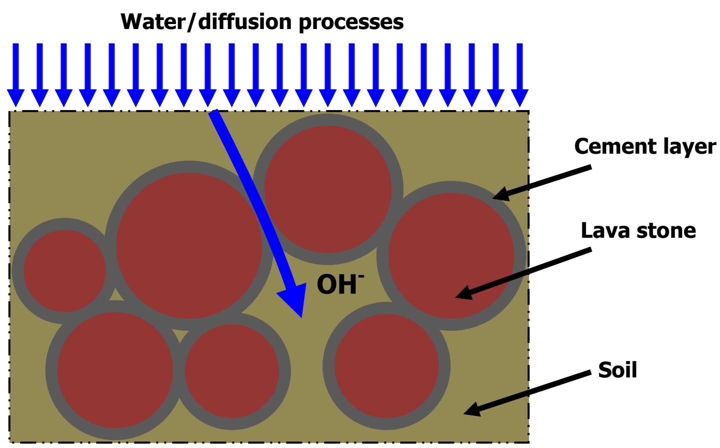

Figure 4.6.3 Schematic presentation of the top layer of the elements and relevant processes.

Concrete is a highly alkaline material (pH of the concrete pore solution ranges from 12.6 to 13.4). Additionally, alkalinity of the bulk concrete matrix results from the composition of cement itself, including the presence of Ca-containing substances. Therefore, with rainfall or artificial watering of the concrete blocks, concentration gradients between the concrete layer, the layer composed from lava stone and the soil will occur. This will result in diffusion processes (eventual leaching), which in turn will promote pH changes in the layers.

In order to study the relevant pH alterations, different pH measurements of the soil and the lava stone were made. The pH was monitored at different time intervals until three months after installation of the soil mixture inside the concrete blocks. To be able to compare the pH changes with the initial values before the installation of plants, control samples of soil were monitored as well. In order to prevent plant intervention on ion absorption some blocks (2 pieces) were maintained free of plants during the experiment. The pH measurements were done with a neutral water solution (distillate water with pH 7). Samples were taken (from soil, lava and cement/concrete) and converted to powder. For an accurate comparison of pH alterations, an identical water/material ratio was used for all tests.

Sampling

Different soil and lava stone samples were taken (10 samples). As an example, the initial soil and soil that was more than three months in the porous concrete layer, as well as initial lava stone and lava stone after three months, are discussed, Figures 4.6.4 and 4.6.5 depict the investigated samples.

Figure 4.6.4 Soil samples from porous concrete layer, photo A is initial soil, photo B soil after three months of installation.

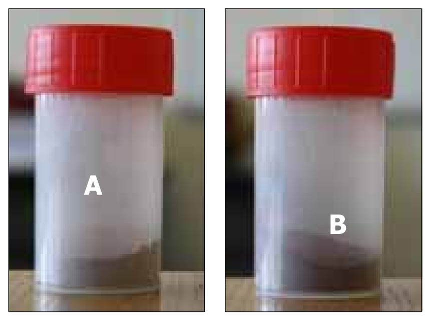

Figure 4.6.5 Photo A; cement sample, photo B; lava stone sample.

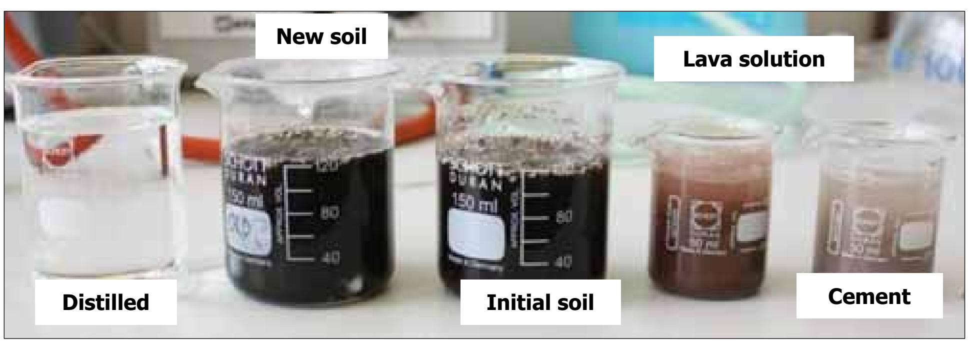

Figure 4.6.6 The received mixtures (pH measurement).

Table 4.6.1 Average pH values of the different samples.

Sample	Powder volume (ml)	Water volume (ml)	pH
Cement	9	45	12.4
Lava stone	9	45	12.2
Initial soil	20	100	7.2
3 months soil from concrete	20	100	9.2
Water	---	150	7

The results from the "pH tests" are summarized in table 4.6.1. It can be concluded that the initial pH of the soil increases (from 7.2 to 9.2) within 3 months after contact with the cement based layer. The change is related to diffusion processes as a result of concentration gradients and pH gradients. Additionally, increase in pH of the soil can be related to leaching of Na^+, K^+ and Ca-bearing compounds from the cement-based layer into the lava layer, containing the soil. The tests are on-going and after completion will be further coupled with EDX (or XRD, XRF) analysis of the dry compounds (before and after pH tests) in order to clarify the exact mechanisms.

Green concrete blocks monitoring

Monitoring of plant growth was done by visual inspections regularly (weekly). Each of the numbered blocks were photographed at the same distance, see figure 4.6.7 for an impression of the test location. The main purpose of the monitoring is to establish which plant species are able to grow in this concrete environment (pH).

Figure 4.6.7 Concrete elements placed in Botanical garden Delft University of Technology.

Thymus praecox

Sedum species

Geranium cinereum subcaulescen

Aubrietia

Asplenium scolopendrium

Asplenium trichomanes

Cymbalaria muralis

Figure 4.6.8 Different types of plant species used for the experiment.

Monitoring plant growth

Figure 4.6.9 shows a *Thymus* sample at the beginning and at the end of the monitoring.

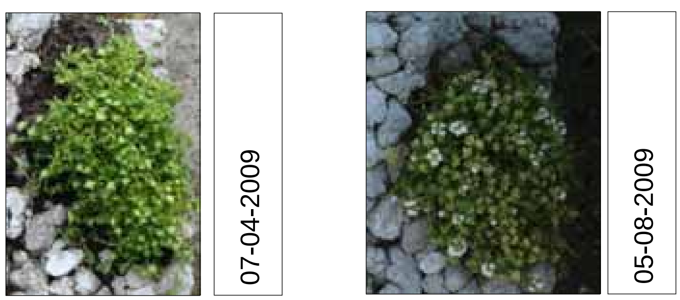

Figure 4.6.9 Development of a Thymus sample on the concrete block.

Figure 4.6.10 shows a *Sedum* sample at the beginning and at the end of the monitoring.

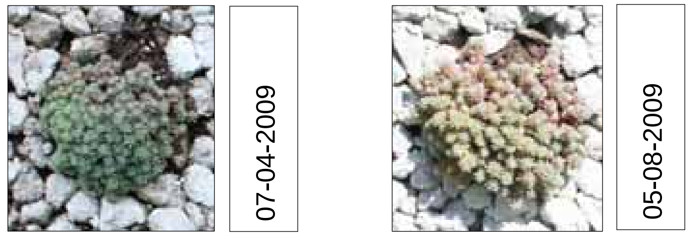

Figure 4.6.10 Development of a Sedum sample.

Figure 4.6.11 shows a *Geranium* sample at the beginning and at the end of the monitoring.

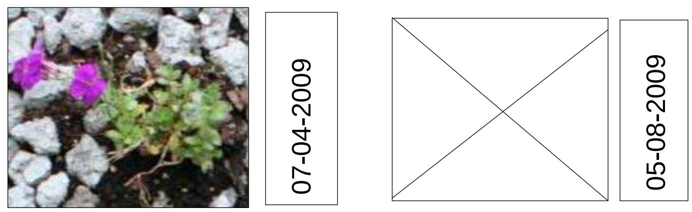

Figure 4.6.11 Development of a Geranium sample.

Figure 4.6.12 shows an *Aubrietia* sample at the beginning and at the end of the monitoring.

Figure 4.6.12 Development of an Aubrietia sample.

Figure 4.6.13 shows an *Asplenium trichomanes* sample at the beginning of the monitoring.

Figure 4.6.13 Development of an Asplenium trichomanes.

Figure 4.6.14 shows a *Cymbalaria muralis* sample at the beginning and at the end of the monitoring.

Figure 4.6.14 Development of a Cymbalaria muralis sample.

From the plant monitoring can be concluded that most of the plant species survived after three months of growth. Nevertheless we see also dying of some plant species in particular on several concrete blocks. Especially the *Aubrietia* and *Geranium* species shows decadency on all of the concrete blocks. *Asplenium scolopendrium* was unfortunately after three weeks already dead, probably the positioning (sun) of the concrete blocks as well as the environment (concrete) was the cause of this extinction. Apparently the *Aubrietia, Geranium* and *Asplenium scolopendrium* species are not suitable for a fresh concrete environment (high pH). As main conclusion can be drawn that *Cymbalaria muralis* and *Sedum* species typically related to wall vegetation are more suitable plant species to let grow on the concrete blocks.

Towards a more technical application of the "green façades" in civil engineering

As previously introduced, concrete is our main building material. Related to civil engineering applications and in particular, reinforced concrete structures, various concerns for maintenance, repair, durability and sustainability are to be addressed. Additionally, "quality of life" is becoming a major issue in modern urban environments. Except the reinforcement corrosion-related durability issues, some important and emerging concerns, related to reinforced concrete are: reduction of the "heat island effect" in hot seasons (and reduction of heat release in cold seasons); reduction of noise transmission, energy savings. Traditionally (and as previously introduced), the aim of "green façades" or "roofs" is to create benefit for both nature and humans. On a more technical basis, energy saving by isolation (in summer periods); micro-climate improvement and capability of plants to adsorb air polluting substances are aimed. All these are very important, but are actually considered to be with a (more or less) aesthetical purpose mainly. Therefore, a combined application of protection techniques for reinforced concrete and green façades, by using an innovative bio-foam cement based layer are briefly presented in what follows, as part of our future research on "green façades" and building materials.

Impressed current cathodic protection (CP) is an electrochemical technique for corrosion control. The principle of CP is to electrically connect the reinforcing steel to the negative and an inert anode to the positive terminal of a direct current (DC) source. The steel becomes a cathode and corrosion is thermodynamically impossible to occur. When a structure is suffering from reinforcement corrosion, the deteriorated concrete over-layer has to be removed, remediation to be performed and an anode to be placed on the exposed surface. Further, the anode has to be covered with a cement-based layer. The hereby proposed innovative solution is to use a *multifunctional, bio-foam cement-based layer* (which can be applied for new structures in the same manner), instead of the conventional one.

The bio-foam/cement based layer is a completely new and innovative approach. The novelty and originality within the development of the "green" CP technique for corrosion control in Civil engineering is the integration of its elements and the application itself. Schematically the approach is depicted in Figure 4.6.15. Some main aspects/innovative solutions per integral part of the "green" CP are:
a) *Photovoltaic cells for CP applications*: the major concern (and loss) with these cells is overheating, which will be hereby reduced when vegetation is in the proximity of the cells;
b) *Bio-foam/cement based layer*: composed of cement, recycled porous aggregate (or lava stone) and bio-foam (UF resin (Urea-formaldehyde), generally used for growing plants). Application over the anode will be achieved via spraying or as a "plaster". The foam fraction itself will be initially saturated in order to prevent ion concentration and water gradients between the hardening cement and the foam phase;
c) *Multifunctional "green" CP*: except corrosion control, will result in: "Clean air": plants as dust and other polluting substances collectors (enhanced effect due to the electrical/electromagnetic field within the running CP);
d) *Improved growing medium* (due to the general anodic reactions in the proximity of plant growth); increased anode efficiency (lower RH in the layer) maintained within the irrigation);
e) *Comfort & Sustainability*: thermo isolation (cooling in summer and heat retain in winter periods) and sound isolation will result from the proven properties of the bio-foam itself: long recognized are heat isolation and excellent sound absorption (in addition to the stability, non-flammability, antibacterial action and bio-degradability of the bio-foam).
f) *Cost-efficiency*: indirectly the self-supported "green" CP system will lead to reduced energy consumption (mainly for heating and cooling with respect to residential buildings).

Summarizing, a multipurpose anode overlay will be developed, serving the purposes of: increased dust collecting, CO_2 reduction, thermo and sound isolation, increased anode efficiency and last but not least aesthetics and comfort purposes. The bio-foam cement based layer can be used for other than the above (CP related) applications – as a finishing overlay for civil engineering structures were corrosion control is not an issue. Indirectly the self-supported "green" CP system will lead to reduced energy consumption (heating and cooling with respect to residential buildings), "green" energy for the CP itself as well.

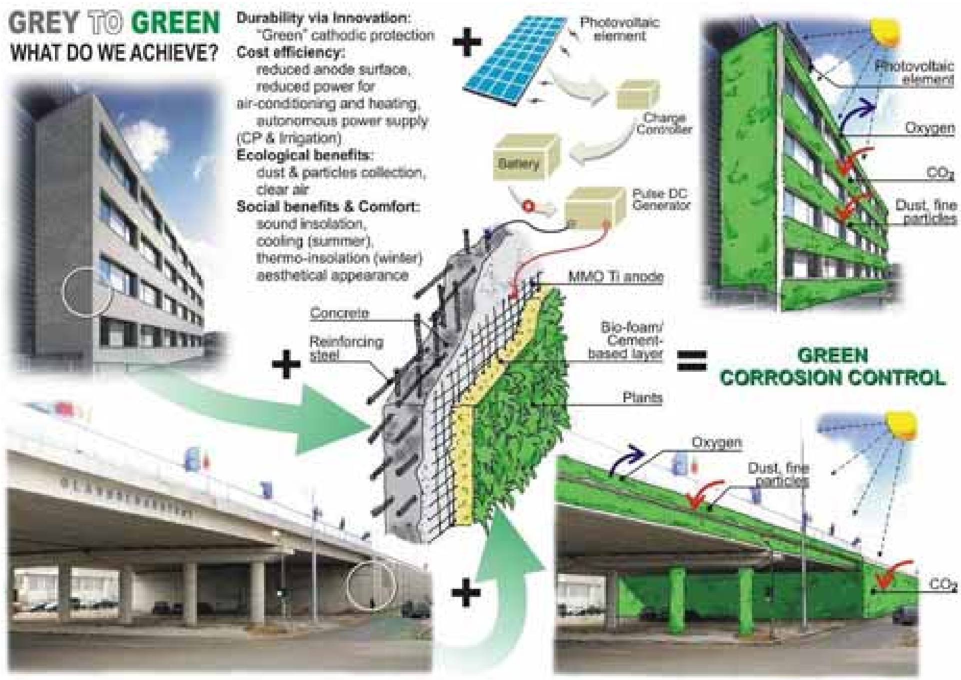

Figure 4.6.15 Schematic presentation of the "green" CP solution for corrosion control (typical examples for application) (figure from the authors).

Conclusions

This work reports on some results from an ongoing investigation of growable concrete and the possibility to let grow plants on building materials. Preliminary results of pH testing and monitoring of the planted concrete blocks shows the possibility that plants can survive on concrete. However the pH measurements show that the pH is increasing over time, this can be devastating for the development of some plant species (species are only suitable if they can grow in basic environments). It shows also the influence of the high concrete pH on the soil pH. Visual inspections shows that the roots of the plants grew according to plan inside the green-(growing)concrete, most of the plants themselves show a healthy development, (some species died due to the raise of the pH or due to lack of water).

Additionally, a brief introduction of a combined approach i.e. purely technical application of maintenance and repair techniques for reinforced concrete structures and "green façades" was presented, highlighting the potential and practical benefits of such integrated solutions.
As main conclusion we can say that the first steps in greening building materials have been made successfully. Further research is needed on the durability aspects of these building materials covered with vegetation.

5 Vertical Green and building physics

5.1 Introduction

In building physics the state and behaviour of the building envelope is analyzed. The building envelope consists of the following components walls (with and without windows), roofs, floors and foundations. In order to build energy efficient buildings it is necessary to understand and predict the heat flow through the building envelope. 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. In the process of building physical design of a building, temperature levels and heat flows must be predicted. With respect to energy, natural resources are limited on earth, it is therefore of interest to find sustainable building technologies. This will involve the right choice of building materials and building components but more important to integrate or combine all of these components to optimalize the building envelope with respect to the thermal behaviour.

Heat and mass (moisture and air) transfer in building structures is basically the direct consequence of differences in temperature, air pressure or moisture conditions (Hagentoft, 2003). The heat that is transferred through solid structures is referred to as transmission. The mechanisms of heat and mass transfer, which must handled in the analyzes of the performances of the building, are directly linked to each other. For instance air that moves will transfer both heat and moisture from one place to another and temperature differences may cause air movements. Within the studies of building physics, all of these processes will take place at normal atmospheric pressure and within a rather limited temperature range, approximately -20 °C to +80 °C (Hagentoft, 2003). To predict how the building envelope will react under different environmental conditions, it is essential to apply mathematics in order to both find simplified "rules of thumb" and for detailed simulations.

In determining the heat flow through constructions it is effective to make a distinction between a steady state and non-stationary situation. We speak of a steady state situation if the temperature and heat flux densities do not change over time. In general, steady-state techniques are useful when the temperature of the material does not change with time. This makes the temperature analysis straightforward (steady state implies constant temperature). However the disadvantage is that a well-engineered experimental setup is usually needed, as will be discussed in paragraph 5.5 of this thesis.

Heat resistance

The heat resistance is a numerical value for the amount of heat per unit time per m^2 which is passed through a structure that is confronted with a specific temperature difference between inside and outside. The total heat resistance of a structure, represented by the symbol R_T, is to add the heat resistance of each of the component parts to each other, and is therefore depending on the material properties of these parts. In composite façade engineering, the air cavity and insulation material is the main contributor to the total heat resistance of a façade. Also the transition resistance is crucial for the heat flow. A transitional resistance is a resistance that should be bridged if a certain heat flow is transferred to an external structure and from there to the open air.

Moisture

Moisture can be transported both in vapour (gas) and liquid (water) phase. Moisture transfer is caused by: diffusion, convection, capillary suction, wind pressure and gravity (Tammes and Vos, 1984; Hagentoft, 2003). The diffusion of vapour is a process of equalization. A difference in vapour concentration results in a net transfer of water molecules to a region with the lowest concentration (Hagentoft, 2003). The interaction of moisture with building materials and components of the envelope influences the thermal performance of buildings. The water vapour content of air, or the humidity by volume is denoted by v (kg/m^3). Since air consists of many gases, each of these gases contributes with its partial pressure to the total air pressure (Hagentoft, 2003). The partial pressure for water vapour is denoted by P_v (Pa) Due to the liquid-gas equilibrium for water, there is a maximum possible water vapour content in thee air (v_s with unit kg/m^3). The humidity by volume at saturation is a function of the ambient temperature. The relative humidity (RH) is defined as:

$RH = v / v_s$ and is often expressed in percentage.

5.2 Plants and their role in (building) physics

Plants take a fundamental place in the food chain, because they are the primary source of organic materials (production of biomass), for animals and humans (consumers). Plants use their leaves to make mainly glucose (carbohydrates) in a light-dependent process known as photosynthesis. Photosynthesis is a photochemical process in which the plant absorbs the light energy into the chlorophyll (leaf green) and carotenoids (yellow-red pigment types) in the leaves. Photosynthesis in leaves synthesizes organic compounds (mainly carbohydrates) by combining carbon dioxide (CO_2) and water (H_2O). The energy needed for this biochemical process is from solar radiation (Feng et al., 2010). The simplified reaction equation of photosynthesis is given by equation (1).

Carbon dioxide + water + light energy → Carbohydrates (mainly glucose) + oxygen

$$xCO_2 + \mathrm{y}H_2O + light\ energy \rightarrow C_6H_{12}O_6 + \mathrm{x}O_2 \qquad (1)$$

In order to get a better understanding of the cooling effect of plants or parts of plants the energy balance of a leaf will be briefly discussed. Most of the absorbed energy comes from shortwave solar radiation (short-wave radiation SR: wave length of about 300-3000 nm). A small portion (approximately 2%), however will be reflected (reflection) or transmitted (transmission), a part is emitted as fluorescence or is used for metabolic processes (Baas et al., 2003). In addition the leaves absorb energy from the long wave infrared radiation from the environment, e.g. the soil.

Plants have a different sensitivity for wavelengths than humans, only a fraction of the light spectrum is used for the growth of plants (photosynthesis), namely the light spectrum between 400 and 700 nm. This is what we call the PAR (PAR = Photosynthetic Active Radiation). Approximately 45% of the overall radiation of light is between 400 and 700 nm. When we talk about PAR we refer to the energy content of light between 400 and 700 nm (in W/m^2).

If no heat loss would occur, the temperature of the water inside the leaves will rise in a very short time to the boiling point. Processes of heat loss therefore play a major role to hold the leaf on an acceptable temperature. The processes that occur are radiation, convection and transpiration. Radiance (emission) occurs through long wave infrared radiation (wavelength approximately 2000-20000 nm). Convection occurs by transfer of molecules in the direction of the temperature gradient by means of air movement (Baas et al., 2003).

On a sunny day the leaf takes a temperature at which the same energy through evaporation (latent heat) and convection (sensible heat) is gathered by the leaf to solar radiation. Plants also evaporate in the night when no solar radiation is absorbed. This is because the exchange of energy through convection is two-way traffic. When a leaf is warmer than the surrounding air, it gives energy to the surrounding air, but when the leaf is cooler it extracts the energy out of the air.

The radiation of the sun is divided into different wavelengths of light. Most of the wavelengths will reach earth as visible light and as infrared and ultraviolet light. When a façade is irradiated by the sun, heat transfer will occur through this façade (Van der Linden et al., 2006). Most of the sun's radiation that is adsorbed by concrete, bituminous materials or masonry is reradiated as sensible heat (infrared light). Greening the surfaces with vegetation to intercept the radiation can reduce the warming of hard surfaces, especially in dense urban areas.

From 100% of sun light energy that falls on a leaf (figure 5.1), 5-30% is reflected, 5-20% is used for photosynthesis, 10-50% is transformed into heat, 20-40% is used for evapotranspiration and 5-30% is passed through the leaf (Krusche et al., 1982). According to Minke and Witter (1982) the following average values for the energy balance of leaves can be extracted: transpiration 30%, reflection 18%, emission 30%, transmission 18% and photosynthesis 4%.

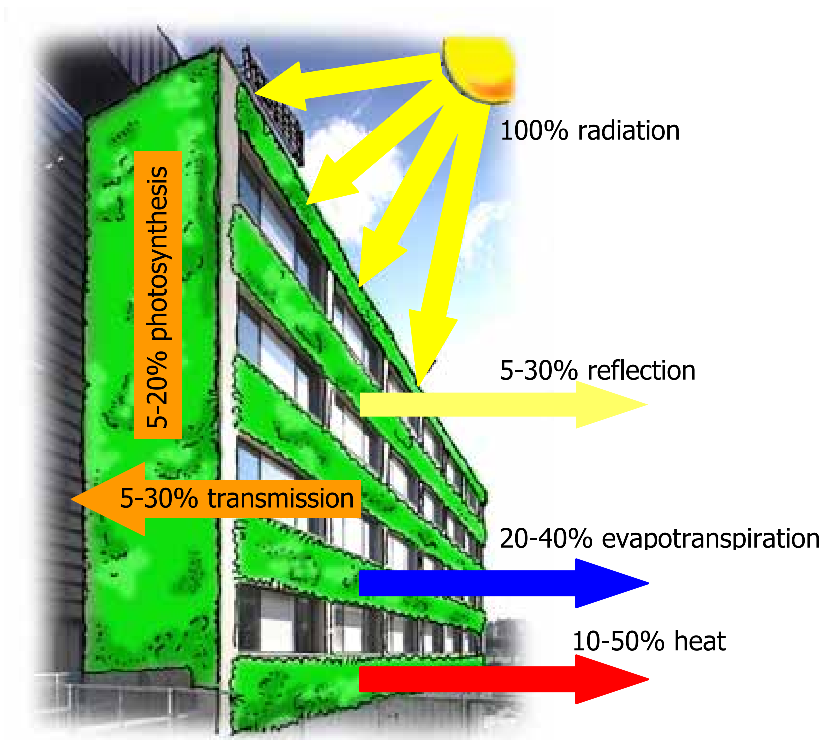

Figure 5.1 Schematisation of the energy balance of vegetation (adapted from Krusche et al., 1982) translated at building level for a green façade.

In the urban area, the impact of evapotranspiration and shading of plants can significantly reduce the amount of heat that would be re-radiated by façades and other hard surfaces. The green plant layer will also reduce the amount of UV light

that reaches building materials. Since UV light deteriorates the material and mechanical properties of coatings, paints, plastics, etc. plants will also have effect on durability aspects. This is a beneficial side effect which will have a cost effective effect on maintenance costs of buildings. The denser and thicker (as a measure for the porosity of the foliage) the plant layer on the green façade, the more beneficial these effects are.
Green façades and roofs reduce the heat transfer through the façade and roof, and as a result will reduce the cooling and heating energy of a building. The main transfer mechanisms of heat through a façade and roof are convection and radiation (Bass et al., 2007). The mechanisms of heat transfer are affected by a green façade and roof, not only by choosing for materials with a higher or lower *R-value*, but also through the evapotranspiration and metabolic processes of plants.

The role of insulation materials and stagnant air layers is to slow down the heat transfer between the interior and exterior of a building, which is a function of the difference between the inside and outside temperatures. An insulation material mitigates the impact of the created temperature difference between inside and outside. In winter conditions the insulation material slows down the rate of heat transfer to the outside. In summer conditions the opposite occurs; it slows down the rate of heat transfer from the outside to the inside. The greening of vertical surfaces has a beneficial effect on the insulating properties of buildings through exterior temperature regulation (Krusche et al., 1982). The insulation value of vertical greened surfaces can be increased in several ways as earlier discussed. According to Peck et al. (1999) it is mainly related to trapping a stagnant air layer inside the foliage, filtering of the suns radiation by the foliage and preventing of moving wind along the façade due to the foliage.

A structure which exits of multiple layers can be considered as a series system (figure 5.2). This means that the heat flow which passes through a construction will encounter for each individual layer a "heat" resistance. A series system is a tool to reduce the complexity of the network and simplifies the analysis (Hagentoft, 2003). The tool is valid for any sequence of resistances in series (without other connections at the internal nodes between the resistances). For each individual material layer the resistance can be calculated as the ratio between layer thickness and the thermal conductivity. Numbering (1, 2, ….., n) takes place from outside to inside for each material layer (resistance) and the following heat resistances can be described between both surfaces of the construction according to relation (1):

With $R_1 = \frac{d_1}{\lambda_1}$; $R_2 = \frac{d_2}{\lambda_2}$; ....; $R_n = \frac{d_n}{\lambda_n}$ (1)

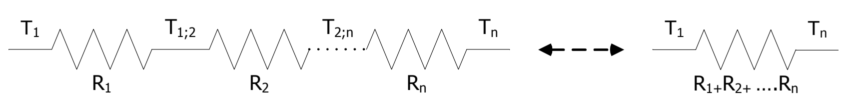

Figure 5.2 Thermal resistances of separate layers of a construction can be schematized as a (electrical) series system.

According to the described series system for a non greened construction one can add the resistances for vegetation (direct and indirect green) and for living wall systems vegetation plus materials, as illustrated in figures 5.3 and 5.4.

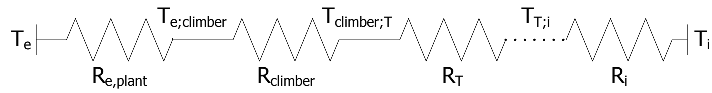

Figure 5.3 Illustration of the resistances in series for a construction covered with a (directly) green plant layer.

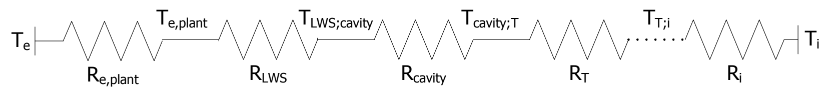

Figure 5.4 Illustration of the resistances in series for a construction covered with a living wall system (LWS).

With	T_i	interior air temperature
	R_i	interior surface resistance
	R_T	thermal resistance construction
	$R_{climber}$	thermal resistance climbing plant
	R_{cavity}	resistance "extra" created cavity
	R_{LWS}	thermal resistance living wall system
	$R_{e;plant}$	changed exterior surface resistance due to foliage
	T_e	exterior air temperature

The thermal resistance of the construction influences the temperature gradient through the construction. The following notations can be used to describe the temperatures at the locations of the boundary surfaces of the different layers:

Exterior surface:	$T_{e,surface}$
Interface between layer 1 and layer 2:	T_1
Interface between layer 2 and layer 3:	T_2
Interface between layer n-1 and layer n:	T_n
Interior surface:	$T_{i,surface}$

For steady state conditions, the rate of heat flow per unit area through the building's fabric with an *R-value*, an indoor surface temperature ($T_{i,surface}$) and an outdoor surface temperature ($T_{e,surface}$) is given by equation (2):

$$q=\frac{T_{e,surface}-T_1}{R_1}=\frac{T_1-T_2}{R_2}=....=\frac{T_{n-1}-T_{i,surface}}{R_n} \qquad (2)$$

The temperature difference between the exterior and interior surfaces ($T_{i,surface}$-$T_{e,surface}$) of the different structure layers is divided in proportion to their thermal resistance. Equation (2) can also be written as: $q=\frac{T_{i,surface}-T_{e,surface}}{R_1+R_2+....+R_n}$ (3)

The total thermal resistance (R_T) of a construction (being the sum of all the thermal resistances from the inside to the outside) can be calculated according to NEN-EN-ISO 6946:2008 by (see figure 5.5): $R_T=R_i+....R_n+R_e$

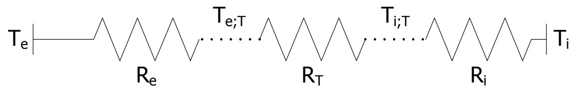

Figure 5.5 thermal resistances in series from outside to inside with R_T the total resistance of separate layers of a construction.

The temperature at the interface between layer n and layer n+1 can be calculated according to equation (4):

$$T_n=T_i-\frac{R_i+....+R_n}{R_T}\left(T_i-T_e\right) \quad (4)$$

And the rate of heat per unit area according to equation (5):

$$q=\frac{T_i-T_e}{R_i+....+R_n+R_e}=\frac{T_i-T_e}{R_T}=\frac{1}{\sum R_T}\Delta T \quad (5)$$

To calculate the heat flow rate through a building's fabric, it is allowed to exchange the interior temperature (T_i), with the interior surface temperature ($T_{i,\ surface}$) and to exchange the exterior temperature (T_e), with the exterior surface temperature ($T_{e,\ surface}$). For steady state conditions, the rate of heat per unit area (q) between each surface must be the same (Tammes and Vos, 1984; Hagentoft, 2003), figure 5.6 illustrates the rate of heat for a bare, a greened façade and a façade covered with a typical LWS concept configuration.

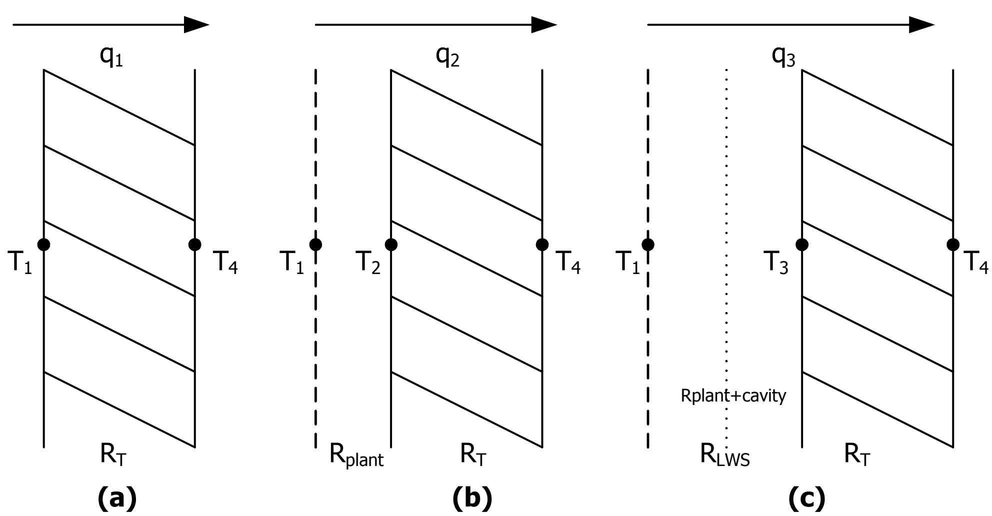

Figure 5.6 Illustration of calculating the heat flow through a bare façade (a), directly greened façade (b) and a façade covered with a LWS panel (c).

Figure 5.6 shows the illustration of the calculation of plants and LWS concepts thermal resistance. Fig 5.6a shows a façade element without vegetation. In figure 5.6b, the vegetation is assumed to be an additional homogeneous[1] layer and the temperature gradient of T_1 and T_2 is caused by the presence of the homogeneous layer. Figure 5.6c shows a typical LWS concept configuration; again the vegetation and the materials used for the pre-vegetated modules are assumed to be homogeneous. The temperature gradient of T_1 and T_3 is caused by the presence of the homogeneous layer. In figure 5.6, T_1 (K) is the surface temperature; T_2 an T_3 (K) the surface temperature of a façade covered with plants or a LWS concept; T_4 (K) the interior surface temperature of the building; q_1 (W/m^2) the rate of heat per unit area through the façade without greenery; q_2 (W/m^2) the rate of heat per unit area through the façade with a plant cover; q_3 (W/m^2) the rate of heat per unit area through the façade with a LWS module placed in front of the façade; R_T (m^{2}K/W) is the total thermal resistance of the basic façade package; R_{plant} (m^{2}K/W) the total thermal resistance of the vegetation layer; and R_{LWS} (m^{2}K/W) the total thermal resistance of a LWS module included the "extra" created cavity between module and façade. For the bare façade can be found:

$$q_1 = \frac{(T_1 - T_4)}{R_T} \tag{6}$$

As for the direct greened façade can be found:

$$q_2 = \frac{(T_1 - T_4)}{R_{plant} + R_T} = \frac{(T_1 - T_2)}{R_{plant}} = \frac{(T_2 - T_4)}{R_T} \tag{7}$$

For a façade covered with LWS panels can be found:

$$q_3 = \frac{(T_1 - T_4)}{R_{LWS} + R_T} = \frac{(T_1 - T_3)}{R_{LWS}} = \frac{(T_3 - T_4)}{R_T} \tag{8}$$

Via equation (7) the thermal resistance of the plant layer for a direct greened façade can be derived (eq. 9), the same can be found for the thermal resistance of a façade covered with a LWS concept (eq.10):

$$R_{plant} = R_T \frac{(T_1 - T_2)}{(T_2 - T_4)} \tag{9}$$

$$R_{LWS} = R_T \frac{(T_1 - T_3)}{(T_3 - T_4)} \tag{10}$$

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[1] A homogeneous layer is a layer of constant thickness having thermal properties which may be regarded as being uniform.

5.3 Thermal aspects of vertical green

5.3.1 The theoretical influence of a "green" exterior surface resistance

The heat exchange between surfaces and the environment is created both by radiation and convection. With convection primarily the wind velocity along the construction surface plays an important role. Increasing the wind velocity will lead to a larger convective heat exchange between the surrounding air. The size of the heat flow through a construction depends therefore on the wind velocity along the (mainly the exterior) surfaces. The average density of the heat flow rate and the difference in ambient temperature (or surface temperature) between the inside (T_i) and outside (T_e) of the structure can be simplified by modification of equation (5):

$$q=U\left(T_{i,surface}-T_{e,surface}\right) \qquad (11)$$

With $U=\frac{1}{R}$

The exterior and interior surface temperature is influenced as mentioned before by the wind velocity. The wind velocity that is supposed to influence the exterior surface resistance is defined in NEN-EN-ISO 6946:2008. According to the standard, a wind velocity of 4.0 m/s along the exterior surface and a maximum of 0.2 m/s along the interior surface of a construction is used.
For exterior surfaces NEN-EN-ISO 6946:2008 applies a heat transfer coefficient at 4.0 m/s of: α_e =20 W/m^{2}K (convection) + 5 W/m^{2}K (radiation) = 25 W/m^{2}K

For interior surfaces NEN-EN-ISO 6946:2008 a heat transfer coefficient determined at 0.2 m/s of wind velocity: α_i =3 W/m^{2}K (convection) + 4.8 W/m^{2}K (radiation) = 7.8 W/m^{2}K.

Table 5.2 Design values for the heat transfer coefficient (α).

Symbol	Interior (W/m^2·K)	Exterior (W/m^2·K)
$\alpha_{convection}$	3	20
$\alpha_{radiation}$	4.8	5
α_{total}	7.8	25

The thermal resistance (symbol R; unity m^{2}K/W) can be found out the reciprocal of α_{total} (table 5.3).

Table 5.3 Conventional surface resistances according to NEN-EN-ISO 6946:2008.

Surface resistance (m^2·K/W)	Horizontal direction of heat flow
R_i	0.13
R_e	0.04

As previously described, the heat transfer coefficient (α_e) for the outside of a structure, is mainly determined by the influence of the wind velocity along the exterior surface. The current standardisation assumes a wind speed of 4 m/s for calculating the heat transfer coefficient. Green façades, however, change the wind velocity and its transfer coefficient for the underlying construction material. The leaves (foliage) of plants create an almost stagnant layer of air or reduce the wind strength proportional (Eumorfopoulou et al., 1998 and 2009; Perini et al., 2011). This foliage layer works beneficial on the convection part of the exterior heat transfer coefficient because it is directly influenced by the reduced wind speed. Due to the filtering aspect of the foliage, wall surfaces are also protected against long wave radiation by the reflective properties of leaves, the evaporation of the foliage and the convection of the energy adsorbed by the plants for their growth and biological functions (Eumorfopoulou et al., 2009). On this way also the radiation part of the heat transfer coefficient is influenced and can be lowered owing to the use of vegetation.
As can be found in the regulation NEN 1068; α_e =20 W/m^{2}K (convection) + 5 W/m^{2}K (radiation) = 25 W/m^{2}K. The convection part is the largest share in the total heat transfer coefficient. Rath and Kießl (1989) found in their research that a well developed green façade (both *Hedera and Parthenocissus*) produces a stagnant wind zone near the wall surface. They also found that the circulation velocity between the foliage was less than 0.5 m/s. According to the calculation method given in the standards, using figure 5.7 and the wind speed of 0.5 m/s found by Rath and Kießl (1989), it can be found that $\alpha_{convection}$ will become ≈ 6 W/m^{2}K.

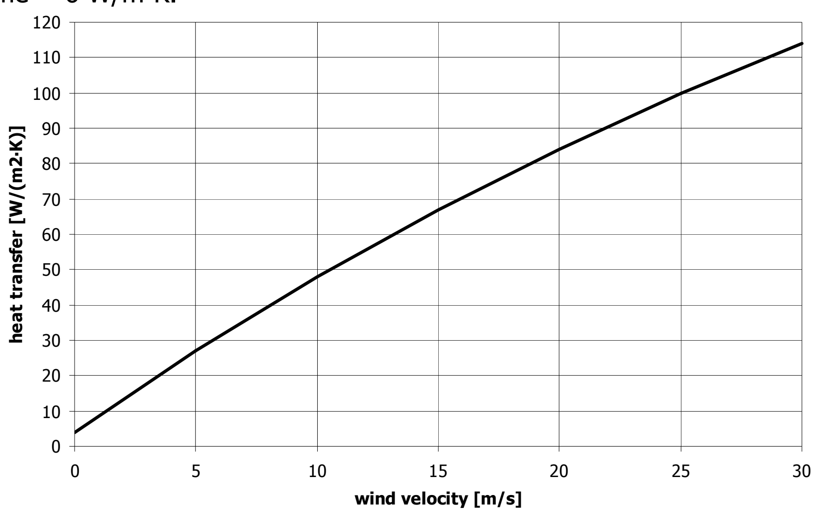

Figure 5.7 The heat transfer coefficient (α_c) for convection as function of the wind velocity (V) from Tammes and Vos (1984).

Eumorfopoulou et al. (2009) found for a planted roof the hemispherical emissivity is $\varepsilon_{radiation}$ ≈ 0.3, which is obvious less compared with a bare surface

$\varepsilon_{radiation} \approx 0.9$. Although the found hemispherical emissivity is valid for a green roof it is due to the contribution of vegetation that it is lower than a bare surface. It seems therefore plausible that the hemispherical emissivity of $\varepsilon_{radiation} \approx 0.3$ is also applicable for green façades. Given the emissivity (0.3), the Stefan-Boltzmann constant ($56.7 \cdot 10^{-9}$) and a mean thermodynamic temperature of the surroundings of 293 K, this will lead to a lower radiative coefficient of $\alpha_{radiation} \approx 1$ W/m²K. On the basis of above discussed exterior heat transfer coefficient (both the convective and radiative part) a new exterior heat transfer ($\alpha_{green\ facade}$) can be determined. The renewed exterior heat transfer coefficient ($\alpha_{green\ facade}$) in the case of a well developed green façade will be: $\alpha_{green\ facade} = 6$ W/m²K (convective) + 1 W/m²K (radiative) = 7 W/m²K

The exterior surface resistance to work with:

$$R_{green\ facade} = \alpha^{-1}_{green\ facade} = 0.14 \text{ m}^2\text{K/W}$$

If the wind speed is 0.5 m/s one can also found via figure 5.8 that the exterior heat resistance will become 0.11 m²K/W, this is without the influence of plants on the adsorption of solar radiation. The exterior heat resistance found with figure 5.8 is therefore partial to the approach of calculating the convective and radiative coefficient separately.

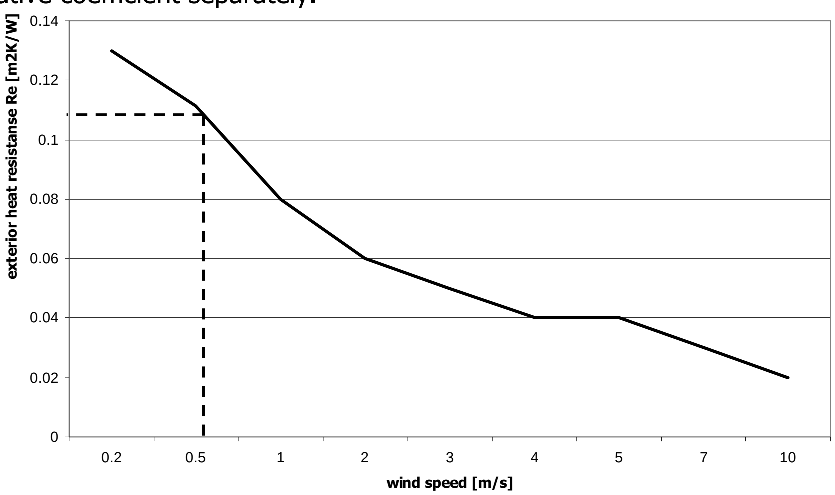

Figure 5.8 The influence of wind speed on the exterior heat resistance R_e,. The figure (shown line) is based on table 5.4 according to NEN-EN-ISO 6946:2008.

Table 5.4 Values of R_e at various wind speeds according to NEN-EN-ISO 6946:2008.

Wind speed (m/s)	R_e (m²·K/W)
1	0.08
2	0.06
3	0.05
4	0.04
5	0.04
10	0.02

5.3.2 What does it means to the insulation properties of buildings?

In order to understand the influence of adapting the exterior surface resistance in case of applying green façades a comparison can be made between traditional building principles. A traditional building material used for dwellings is masonry. As example to study the influence of façade greenery on the total thermal capacity a double brick wall, a cavity wall and an insulated cavity wall will be discussed. The used materials in the examples are respectively: masonry, limestone and mineral wool.

1. Double brick wall + climbing plant
2. Cavity wall + climbing plant
3. Insulated cavity wall + climbing plant
4. Double brick wall + LWS (planter boxes)
5. Insulated cavity wall + LWS (planter boxes)

Furthermore it is important to know that in the Dutch building regulation (2003) a minimum for the total thermal resistance is given for building components. The total thermal resistance that is demanded for new or retrofitted buildings is according to the regulation $R_T \geq 2.5$ m^{2}K/W.

The total thermal heat resistance (R_T) of a construction can be calculated according to NEN-EN-ISO 6946:2008 by the following equation (12):

$$R_T = R_i + R_1 + R_2 + \ldots + R_n + \mathrm{R_e} \tag{12}$$

where

R_i	interior surface resistance;
R_e	exterior surface resistance;
$R_1 + R_2 \ldots + R_n$	design thermal resistances of each construction layer;

Not only the total thermal heat resistance of a construction gives important information, but also the thermal transmittance of a construction. The thermal transmittance (U-value) is the rate of transfer of heat through one square meter of a structure divided by the difference in temperature across the structure. The thermal transmittance can be calculated according to NEN-EN-ISO 6946:2008 by the following equation (13):

$$U = \frac{1}{R_T} \tag{13}$$

The lower the U-value of a construction the better the construction is functioning against heat loss through the construction. With other words the higher *R-value* of the construction the lower the thermal transmittance will be.

Example 1.

In the case of a double brick wall (normally older buildings and monuments) we can compare the effect of a normal bare façade or with the case if a climbing plant is used to cover the same type of façade (figure 5.9). In table 5.5 the material resistances are given and the surface resistances for a bare and greened façade (condition that $R_i = R_e$).

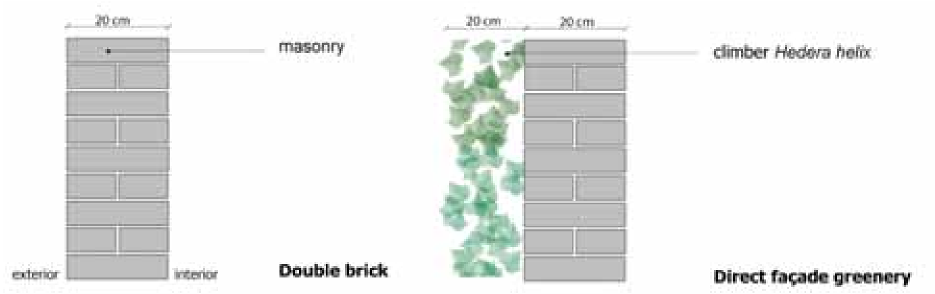

Figure 5.9 Double brick wall with and without a green layer.

From the total resistance in the case of a bare and greened façade we can see that there is a positive proportional (24%) share of the surface resistance influenced by the foliage on the total resistance of the façade.

$\frac{R_{changed} - R_{current}}{R_{current}} \cdot 100\% \Rightarrow \frac{0.46 - 0.37}{0.37} \cdot 100\% = 24.3\%$ is a positive influence for a double brick wall (non insulated).

Table 5.5 Double brick wall and the effect of changing the exterior surface resistance in the case of greening the façade.

Nr.	material layers	d (m)	λ (W/mK)	R_{bare}=d/ λ (m^2K/W)	$R_{greened}$=d/ λ (m^2K/W)
	interior surface resistance			***0.13***	***0.13***
1	masonry	0.20	1	0.20	0.20
2	climbing plant [1]	0.20	***---*** [1]	***---*** [1]	***---*** [1]
	exterior surface resistance [2]			***0.04***	
	(adapted) green façade exterior surface resistance [3]				***0.13***
		0.40			
	Total resistance (R_T)			**0.37**	**0.46**

[1] The resistance of a foliage package is not determined according to literature.

[2] According to the standard NEN-EN-ISO 6946:2008.

[3] Adapted surface resistance due to stagnant air layer.

Example 2.

In the case of a cavity wall without insulation material (figure 5.10) we can do the same calculation (table 5.6) if we change the exterior surface resistance. In the case of comparing the total resistance of a bare and greened façade we can see that there is also a positive influence (15%) of the surface resistance influence on the total resistance of the façade due to the foliage.

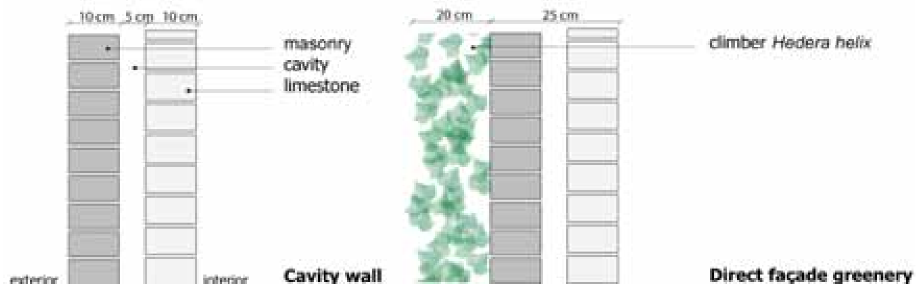

Figure 5.10 Cavity wall with and without a green layer.

$$\frac{R_{changed} - R_{current}}{R_{current}} \cdot 100\% \Rightarrow \frac{0.57 - 0.66}{0.57} \cdot 100\% = 15.7\%$$ is a positive influence for a non insulated cavity wall.

Table 5.6 Cavity wall without insulating material and the effect of changing the exterior surface resistance in the case of greening the façade.

Nr.	material layers	d (m)	λ (W/mK)	R_{bare}=d/ λ (m^2K/W)	$R_{greened}$=d/ λ (m^2K/W)
	interior surface resistance			***0.13***	***0.13***
1	limestone	0.105	1	0.11	0.11
2	cavity	0.05	0.28	0.18	0.18
3	masonry	0.105	1	0.11	0.11
4	climbing plant [1]	0.20	---[1]	---[1]	---[1]
	exterior surface resistance [2]			***0.04***	
	(adapted) green façade exterior surface resistance [3]				***0.13***
		0.46			
	Total resistance (R_T)			**0.57**	**0.66**

[1] The resistance of a foliage package is not determined according to literature.

[2] According to the standard NEN-EN-ISO 6946:2008.

[3] Adapted surface resistance due to stagnant air layer.

Example 3.

In the case of an insulated cavity wall (figure 5.11), it can be directly notified that the insulation material (in this case R=2.86 m^2K/W) contributes considerably to the total resistance of the structure (table 5.7). Insulation material is by far the largest share in the total resistance compared with modifying for example the surface resistances.

The overall advantage left is now only

$\frac{R_{changed} - R_{current}}{R_{current}} \cdot 100\% \Rightarrow \frac{3.52 - 3.43}{3.43} \cdot 100\% = 2.9\%$ very small influence compared with the non insulated cavity wall and a double brick wall.

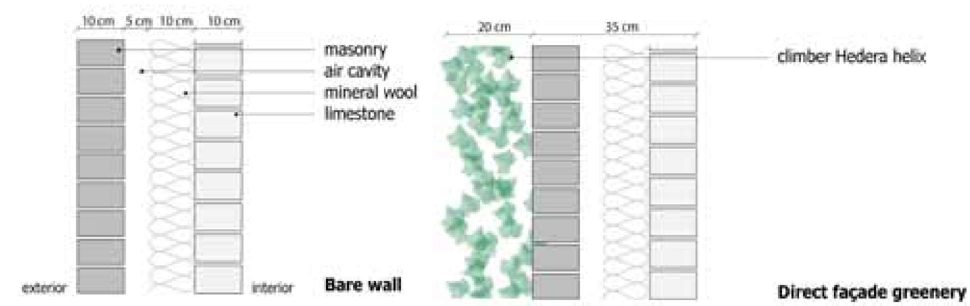

Figure 5.11 Insulated cavity wall with and without a green layer.

Table 5.7 Insulated cavity wall and the effect of changing the exterior surface resistance in the case of greening the façade.

Nr.	material layers	d (m)	λ (W/mK)	R_{bare}=d/ λ (m^2K/W)	$R_{greened}$=d/ λ (m^2K/W)
	interior surface resistance			***0.13***	***0.13***
1	limestone	0.105	1	0.11	0.11
2	mineral insulation	0.1	0.035	2.86	2.86
3	cavity	0.05	0.28	0.18	0.18
4	masonry	0.105	1	0.11	0.11
5	climbing plant [1]	0.20	***---*** [1]	***---*** [1]	***---*** [1]
	exterior surface resistance [2]			***0.04***	
	(adapted) green façade exterior surface resistance [3]				***0.13***
		0.56			
	Total resistance (R_T)			**3.43**	**3.52**

In the discussed examples (1, 2 and 3) it is clear that changing the exterior surface resistance of older and existing buildings (in case of greening the

[1] The resistance of a foliage package is not determined according to literature.

[2] According to the standard NEN-EN-ISO 6946:2008.

[3] Adapted surface resistance due to stagnant air layer.

façades) and buildings without insulation material could lead to energy savings. However for new buildings it is impossible to omit insulation material because of the high contribution to the thermal resistance of a building (and due to fulfilment of the building standards). In example 3 it could be seen that insulation material is superior on the outcome of the thermal resistance and transmittance of a building. Besides that the absence of insulation material violates to the fulfilment of building regulations with respect to compliance on the total heat resistance of a building in all regions across Europe (Eumorfopoulou et al., 2009).

The above discussed thermal performance of a green façade implies that climbers are used in order to cover the façade. As discussed in section 2.2 also living walls systems (LWS) based on prefab panels containing growing substrate are used to cover façades with plants. Due to the characteristics (hydroponic systems, grid and assembly distance and for example moisture protection) of the LWS a cavity is arisen between the planted panel and the façade. The cavity thickness can be easily 50 mm up to 100 mm depending on the used system. Companies provide mainly for aesthetical reasons in finishing of the edges between cavity and façade (figures 5.12-5.15).

Assuming that the panels are mounted well and the edges are finished correctly the cavity can be compared with an "extra" (un)ventilated air layer. For unventilated air layers NEN-EN-ISO-6946:2008 defined thermal resistances for different sizes of air layers (see also table 5.8).

If the joints between the LWS panels are not fixed properly one can speak in the worse case about a well ventilated air layer. NEN-EN-ISO-6946:2008 gives in the case of a well ventilated external air layer an thermal resistance corresponding to the value of R_i (0.13 m^2K/W).

Figure 5.12 Modular living wall system (LWS); space between façade and panel filled with "extra" insulation material. Very suitable principle for retrofitting of older buildings that are less insulated.

Figure 5.13 Living wall system (Fytowall) attached to a façade. One can see clearly the well finished edge. Due to this detailing one can interpret the existing cavity between panel and masonry as a "un ventilated" air layer.

Figure 5.14 Left; modular living wall system; schematization of fixing the panel (planter boxes) against the façade and introducing an air cavity of 40 mm between façade and panel (according to Greenwave systems).

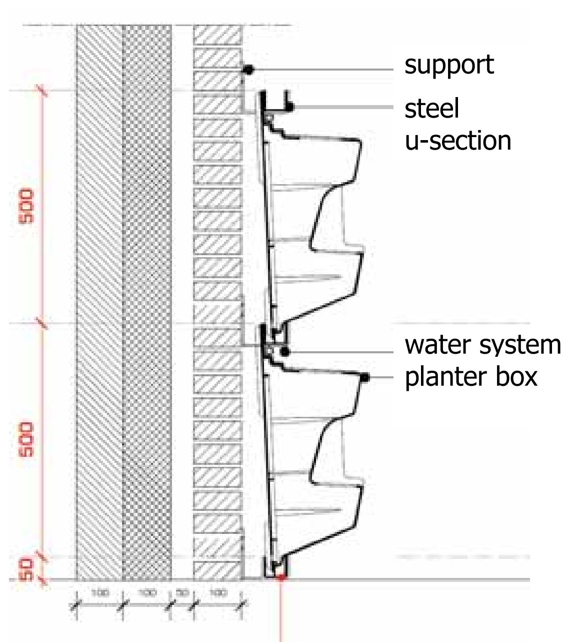

Figure 5.15 Right; modular living wall system (planter boxes) against the façade with closed edges to ensure a stagnant air layer between modules and façade.

Table 5.8 Heat resistances of (un)ventilated air layers according to NEN-EN-ISO 6946:2008.

Thickness air layer (mm)	Heat resistance R ($m^2 \cdot K \cdot W^{-1}$)
0	0.00
5	0.11
10	0.15
15	0.17
20	0.18
25	0.18
50	0.18
100	0.18

This means for the building element that an extra positive resistance layer for the thermal properties can be taken into account.

Example 4. double brick wall + LWS (planter boxes)

The double brick wall again as an example in the case of applying a LWS concept based on planter boxes (figure 5.16); for calculating the thermal properties it is important to consider, if the panels and edges of these panels are closed properly with respect to the resistance for ventilated or unventilated air cavities. In this example only an unventilated cavity will be examined. The thermal resistance of a LWS module is depending on the materials used and the thickness. Planter boxes are filled with wet potting soil, and the thickness of the volume is approximately 15 cm. Given these properties, an assumption can be made for the thermal resistance of planter boxes (wet soil).

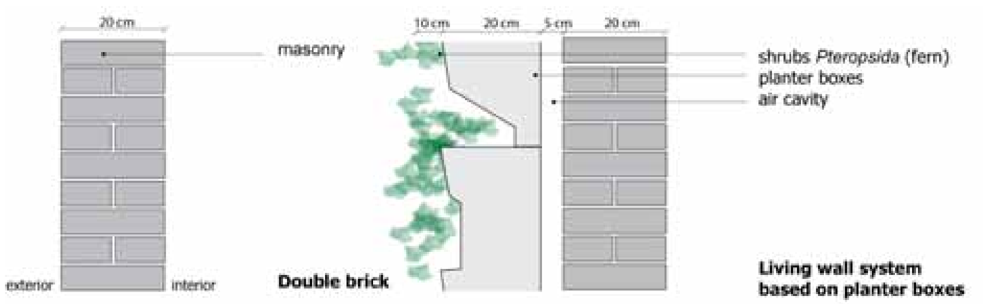

Figure 5.16 Double brick wall retrofitted with a living wall system based on planter boxes filled with soil.

Table 5.9 Double brick wall greened with a living wall system. With adapted exterior surface resistance due to a stagnant air layer between foliage and extra created cavity between LWS panel and façade for calculation.

Nr.	material layers	d (m)	λ (W/mK)	$R_{greened}$=d/ λ (m^2K/W)
	interior surface resistance			***0.13***
1	masonry	0.21	1	0.21
2	cavity (unventilated)	0.05		**0.18**
3	LWS planter boxes [1]	0.20	1	0.20
4	plant layer [2]	0.15	**---**	**---**
	(adapted) green façade exterior surface resistance [3]			***0.13***
		0.41		
	Total resistance (R_T)			**0.85**

The total heat resistance of the described example is increased considerably with 123% compared with the double brick wall without living wall system.

$$\frac{R_{changed} - R_{current}}{R_{current}} \cdot 100\% \Rightarrow \frac{0.85 - 0.38}{0.38} \cdot 100\% = 123\%$$

Example 5. Insulated cavity wall + LWS (planter boxes)

Considering the insulated cavity wall again, it is clear that the contribution of the insulating material is large compared to the other resistances of the layers. The benefit of LWS concepts lay mainly in the "extra" cavity between living wall system module and the façade and the resistance of the panel. According to the calculation a beneficial effect can be gained of 14% in the total heat resistance of the described example.

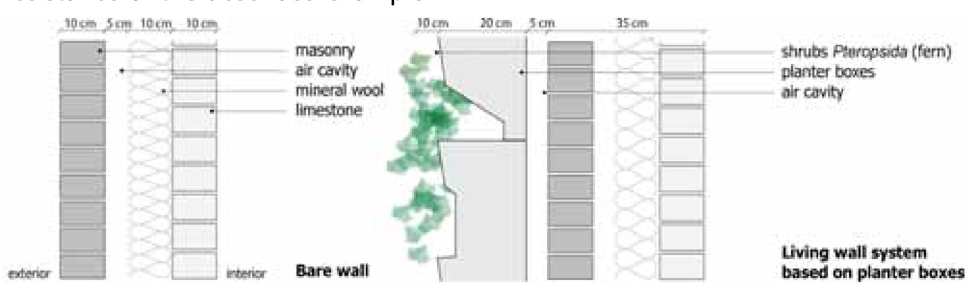

Figure 5.17 Insulated cavity wall with a living wall system based on planter boxes.

[1] Assuming a thermal conductivity of wet soil for LWS concepts.

[2] The resistance of a foliage package is not determined according to literature.

[3] Adapted surface resistance due to stagnant air layer.

Table 5.10 Insulated cavity wall greened with a living wall system. With adapted exterior surface resistance due to a stagnant air layer between foliage and extra created cavity between LWS panel and façade for calculation.

Nr.	material layers	d (m)	λ (W/mK)	$R_{greened}$=d/ λ (m^2K/W)
	interior surface resistance			***0.13***
1	limestone	0.105	1	0.11
2	mineral insulation	0.1	0.035	2.86
3	cavity	0.05	0.28	0.18
4	masonry	0.105	1	0.11
5	cavity	0.05	0.28	0.18
6	LWS planter boxes [1]	0.20	1	0.20
7	Plant layer [2]	0.15	**---**	**---**
	adapted) green façade exterior surface resistance [3]			***0.13***
		0.61		
	Total resistance (R_T)			
				3.90

$$\frac{R_{changed} - R_{current}}{R_{current}} \cdot 100\% \Rightarrow \frac{3.90 - 3.43}{3.43} \cdot 100\% = 14\%$$

Beside the "extra cavity between façade and living wall system also positive effect of the positioning of the substrate can be mentioned, since the substrate of many manufactures are build up of mineral wool, foam or soil mixtures, the mass of these substrates contributes also to the thermal resistance of buildings.

5.3.3 Reflection and summary of the theoretical calculations

Taking into account the discussed examples for calculating the theoretical heat resistance, an overview is given in table 5.11 for the percentages of increase per construction type. The effect of changing the exterior surface resistance coefficient (R_e) in the case of applying a climbing plant (directly) is found to be smaller when the thermal resistance of the façade increases. This means that the effect of insulation material is superior for the thermal behaviour of the construction.

Table 5.11 Summarized improvement of the thermal resistance of a construction by adding a green layer, either with a climbing plant or with a living wall concept.

construction	influence of greening type on the *R-value*	
	climbing plant	*Living wall system (LWS)*
double brick wall	24.3%	123%
cavity wall	15.7%	45%
insulated cavity wall	2.9%	14%

[1] Assuming a thermal conductivity of wet soil for LWS concept based on planter boxes

[2] The resistance of a foliage package is not determined according to literature.

[3] Adapted surface resistance due to stagnant air layer

The same trend can be found for the case of applying living wall concepts against a façade. Due to the extra materials used for these systems the properties regarding the thermal aspects are noteworthy improved, for the insulated cavity wall in this case still 14% of improvement for the total thermal resistance can be achieved. In addition, it can be concluded that for retrofitting of older (especially in the case of double brick façades) constructions a considerably improvement can be achieved by adding a vertical greening system against the (existing) structure, respectively 24.3% can be reached for a green system based on a climber and 123% for green system based on a living wall concept. These improvements on the thermal resistance imply energy savings for heating and cooling at the building level.

The examples discussed in paragraph 5.3.2 are supposed to reflect the current method for building and retrofitting of structures by adding vertical greening systems. Emphasizing *"**by adding**"* because, the current construction methods aimed to attach vertical greening systems on already finished façade systems. However this means that in the case of applying living wall concepts, something can be improved in the building process, taking into account the characteristics of living wall systems as described in paragraph 2.4. This approach results in combining of functionalities to improve the quality of the building cycle. Taking these remarks into account a hypothesis can be formulated.

Is there a possibility to build and create a green building envelope with living wall systems, by reducing materials, combining of functionalities and to fulfil still the thermal properties of the construction?

Based on the findings out of Chapter five and six, this new building philosophy can enhance omitting of the external masonry to save on building costs, on the environmental building impact and to ensure that the building physic aspects of the façade still agrees with the building regulations (Bouwbesluit, 2003).

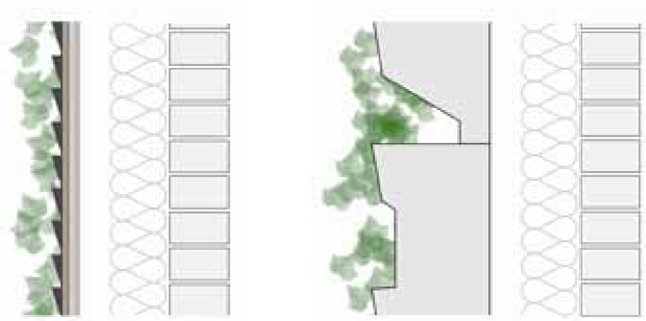

Figure 5.18 Integration of living wall concepts through omitting of the exterior façade cladding material. Via this method, material savings and reduction of the construction thickness could be achieved. This means that creating a green building envelope opens the door for an innovative approach in sustainable building.

Regarding a theoretical calculation for the thermal resistance (*R-value*) of a integrated vertical greening system (LWS based on planter boxes), with the same approach as used for the examples in paragraph 5.3.2, will still lead to an improvement (5%) of the total thermal resistance compared to an traditional insulated façade (no green) as can be seen according to table 5.12.

Table 5.12 Integration of a living wall concept based on planter boxes (for example right drawing of figure 5.18). With adapted exterior surface resistance due to a stagnant air layer between the foliage.

Nr.	material layers	d (m)	λ (W/mK)	R_m=d/ λ (m^2K/W)
	interior surface resistance			***0.13***
1	limestone	0.105	1	0.11
2	mineral insulation	0.1	0.035	2.86
3	cavity	0.05	0.28	0.18
4	LWS planter boxes [1]	0.20	1	0.20
5	plant layer [2]	0.15	---	---
	(adapted) green façade exterior surface resistance [3]			***0.13***
		0.455		
	Total resistance (R_T)			
				3.61

$$\frac{R_{changed} - R_{current}}{R_{current}} \cdot 100\% \Rightarrow \frac{3.61 - 3.43}{3.43} \cdot 100\% = 5\% \text{ benefit}$$

Taking into account the cost savings due to less material needed, that the integrated façade design is still in accordance to the standards with respect to the thermal properties and that in addition a reduction of the environmental load of the façade occurs, it is a reliable choice to build vertical greened surfaces on this innovative method.

[1] Assuming a thermal conductivity of wet soil for the LWS concept based on planter boxes.

[2] The resistance of a foliage package is not determined according to literature.

[3] Adapted surface resistance due to stagnant air layer.

5.4 Vertical greening systems and their effect on air flow and temperature near the façade

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K. Perini[1], M. Ottelé[2], A.L.A. Fraaij[2], E.M. Haas[2], R. Raiteri[1]
[1] Faculty of Architecture, University of Genoa
Stradone S. Agostino, 37 - 16123 Genoa, Italy
[2] Faculty of Civil Engineering and Geosciences, Delft University of Technology
Stevinweg 1, 2628 CN Delft, P.O. Box 5048, The Netherlands.
Corresponding authors: katiaperini@hotmail.com, M.Ottele@tudelft.nl

Abstract
The use of horizontal and vertical greening has an important impact on the thermal performance of buildings and on the effect of the urban environment as well, both in summer and winter. Plants are functioning as a solar filter and prevent the adsorption of heat radiation of building materials extensively. Applying green façades is not a new concept; however it has not been approved as an energy saving method for the built environment. Vertical greening can provide a cooling potential on the building surface, which is very important during summer periods in warmer climates. The cooling effect of green roofs as well as green façades have a positive influence on reducing the urban heat island effect and has also an impact on the inner climate in the building by preventing warming up the façade. In colder climates evergreen species create an external insulation layer and contribute to energy savings and loss of heat. In this study an analysis of the effect on air flow and (air and surface) temperature of vertical greening systems on the building level is presented. An experimental approach was set up to measure the temperature (air and surface) and the air flow near and on different types of green façades and a living wall system to evaluate the influence of wind velocity and its effect on the thermal resistance. A comparison between measurements on a bare façade and a plant covered façade has taken, in the beginning of autumn, to understand the contribution of vegetation to the thermal behaviour of the building envelope.

Keywords: façade greening, living wall systems, air flow, temperature, energy savings, sustainability

Introduction
The integration of vegetation on buildings, through green roofs or vertical greening, allows obtaining a significant improvement of the building's efficiency, ecological and environmental benefits. The benefits gained thanks to the use of vegetation are the subject of studies and researches starting from the seventies

(Bellomo, 2003). During this period the first projects which revolved around nature and the environment emerged such as the work of the American architect James Wines who is associated with the SITE group, Emilio Ambasz, Rudolf Doernach, and Oswald Mathias Ungers.
Green façades and living wall systems (LWS) offer numerous ecological and environmental benefits, can have a positive influence on the comfort and well being in and around the building, besides social and aesthetical value (Bellomo, 2003). The ecological and environmental benefits of vertical greening systems, as for green roofs, concern the reduction of the heat island effect in urban areas, the air quality improvement (Ottelé, 2010; Sternberg et al., 2010) and energy savings. In fact both the growing medium and the plants themselves provide insulation and shade which can reduce, especially in Mediterranean area, energy for cooling (Wong et al., 2009).

Starting from climbing plants planted at the base of building façades, diffuse in traditional architecture since 2000 years ago, there are now several different ways for vertical greening. The many systems available on the market can be classified into façade greening and living walls systems (Köhler, 2008).
Green façades are based on the use of climbers (evergreen or deciduous) attached themselves directly to the building surface (as in traditional architecture), or supported by steel cables or trellis. Living wall systems, which are also known as green walls and vertical gardens, are constructed from modular panels, each of which contains its own soil or other growing medium (soil, felt, perlite, etc) based on hydroponic culture, using balanced nutrient solutions to provide all or part the plant's food and water requirements (Dunnet and Kingsbury, 2004).
Living wall systems and green façades have different characteristics that can have influence on some of the benefits like cooling and insulating properties. This comes, among other things, due to the thickness of the foliage (creating a stagnant air layer and shading the façade), water content, material properties and possible air cavities between the different layers. The role of stagnant air layers is to slow down the rate of heat transfer between the inside and outside of a building.
By constructing green façades and green roofs great quantities of solar radiation will be absorbed for the growth of plants and their biological functions. Significant amounts of radiation are used for photosynthesis, transpiration, evaporation and respiration (Krusche et al., 1982). A part of (5-30%) the remaining solar radiation is passing through the leaves and affects the internal climate of buildings when it passes the façade or roof. Especially in dense and paved urban areas, the impact of evapotranspiration and shading of plants can significantly reduce the amount of heat that would be re-radiated by façades and other hard surfaces. At the building level, as a consequence, every decrease in the internal air temperature of 0.5 °C can reduce the electricity use for air conditioning up to 8% (Dunnet and Kingsbury, 2004).
Covering façades on outside walls with leaves, also known as green façades or vertical greening is discussed in many studies. Field measurements on a plant covered wall and a bare wall by Bartfelder and Köhler (1987) shows a temperature

reduction at the green façade in a range of 2-6 °C compared with the bare wall. Also Rath and Kießl (1989) measured differences in the temperature gradient across a green covered wall. The corresponding factor in both researches is that at 1 m in front of the vegetation layer no temperature differences were measured between the greened and non-greened façades. However the temperature difference found in both investigations (conducted in Germany) at the wall surface between a greened and non greened façade is approximately 6 °C. Another recent study by Wong et al. (2009) on a free standing wall in Hortpark (Singapore) with vertical greening types shows a maximum reduction of 11.6 °C. This means that a greened façade adsorbs less heat then a non greened façade and reveals in less heat radiation in the evening and night.
The thermal transmittance of a construction is among other things dependant on the wind velocity that passes along the surface of a construction. The current Dutch standardisation NEN-EN-ISO 6946:2008 assumes an average wind speed of 4.0 m/s year round on the exterior surface for calculating the heat transfer coefficient. For interior surfaces the standardisation applies 0.2 m/s along the wall surface. Green façades, however, change the wind velocity on the underlying exterior construction material. According to literature it is claimed that leaves (foliage) of plants create an almost stagnant layer of air or reduce the wind strength proportional (Krusche et al., 1982; Rath and Kießl, 1989; Eumorfopoulou and Aravantinos, 1998; Peck et al., 1999), values however of these effects are missing or hardly known in literature.

In this study three common systems for vertical greening of buildings situated in Delft, Rotterdam and Benthuizen (The Netherlands) are considered and analyzed (figure 5.4.1):

1. a direct façade greening system
2. an indirect façade greening system
3. a living wall system based on planter boxes filled with potting soil

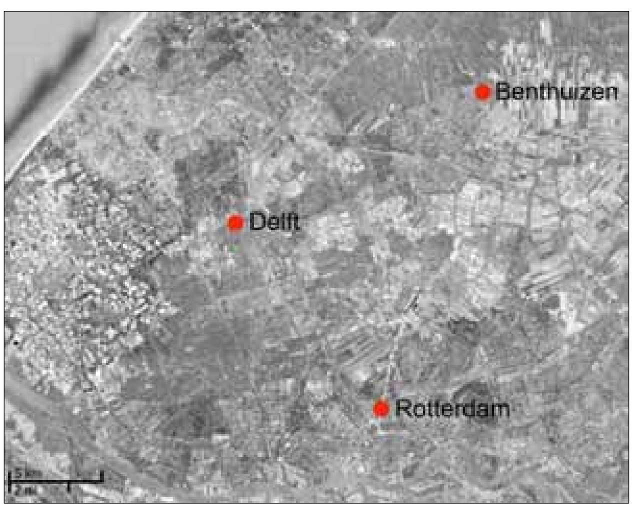

Figure 5.4.1 Locations of the vertical green systems analyzed.

Aim of the study and research questions

There are claims in literature (Krusche et al., 1982; Minke and Witter, 1982) about the insulation properties of greening façades due to a reduction of the wind speed which can cause a possible stagnant air layer or an "extra" air cavity; however these effects are not quantified yet. Therefore the aim of this study is to quantify the above described possible effects. Beside this the objective of the quantification is to evaluate the potential energy savings (energy needed for heating and cooling) with different vertical greening systems due to the increase of the insulation properties of buildings.

Since the aim of this research is to measure the possible reduction of the wind velocity and (air and surface) temperature by different green concepts (direct, indirect and LWS), the following research questions have been formulated:

- Is there a difference in wind speed reduction between different greening systems?
- Is there a difference between air temperatures in front of a bare façade compared with a greened one and between the surface temperatures of the bare and greened façades?

Materials and methods

The chosen greening systems for this research are based on different characteristics such as materials used, plant type and configuration. Due to the characteristics of each investigated greening system it is hypothesized that there is a difference on the microclimate (air-, surface temperature and wind speed) around and in, behind the green walls. The locations of the three façades investigated are all in the Netherlands (province Zuid-Holland) and are not further away than approximately 20 km from each other (figure 5.4.1).

The direct façade greening (figure 5.4.2a), situated in Delft on a 1920 building, consists of a well grown evergreen climber *Hedera helix*, attached directly to the building surface and planted at the base of the greened façade. The second system analyzed in this study is based on an indirect façade greenery (figure 5.4.2b) situated on the façade of 280 m^2 of a residential building from the seventies in Rotterdam. This system is constituted by aluminium pots, filled with soil, placed at several heights and connected to steel frames, acting as support for evergreen climbing plants (*Hedera helix*, *Vitis*, *Clematis, Jasmine and Pyracantha*) with a computer-controlled system for water and nutrients. The third investigated greened façade, a living wall system (figure 5.4.2c), located in Benthuizen, is based on plastic modules (HDPE), filled with potting soil and planted with several evergreen species (no climbers), with a computer-controlled system for water, nutrients and drainage.

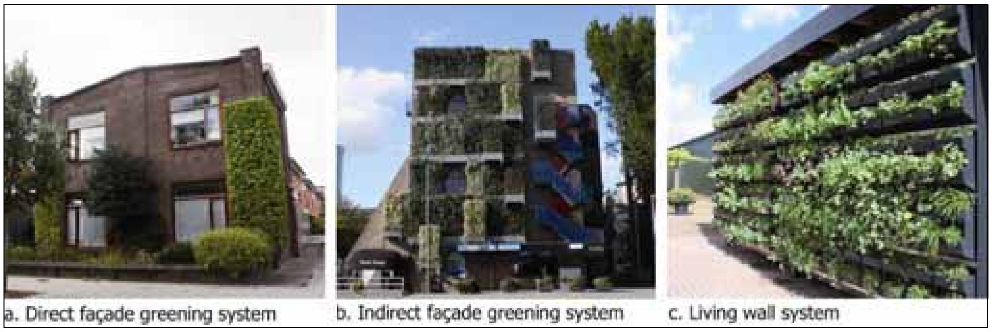

Figure 5.4.2 Vertical green systems analyzed in this study.

All of the air-, surface temperature and wind measurements are done from September till end of October 2010, during days without rain or extreme high wind speeds (above 10 m/s). Measurements have been done between 12:00 and 15:00 hours.

The period has been chosen for the experiment due to the main interest in measuring the wind flow and the importance of taking data during a cooler period.

Description of the greening systems analyzed:

1. Direct façade greening system (Delft), figure 5.4.2a
   Orientation: North-West
   Plant type: climber species of *Hedera helix*
   Plant condition: well grown and covered façade (covering thickness +/- 20 cm)
   Plant age: older than 25 years
   Building material façade: masonry (clay bricks)
   Location: urban area

2. Indirect façade greening system (Rotterdam), figure 5.4.2b
   Orientation: North-East
   Plant type: climber species of *Hedera helix*
   Plant condition: well grown, not completely covered façade (covering thickness +/- 10 cm)
   Plant age: between 2 and 3 years old
   Supporting material: steel frame/mesh
   Air cavity between façade and leaves: 20 cm
   Building material façade: masonry (clay bricks)
   Location: dense urban area (inner city)

3. Living wall system (Benthuizen), figure 5.4.2c
   Orientation: Western
   Plant type: different evergreen plant species (no climbers)
   Plant condition: well grown, not completely covered (covering thickness +/-10 cm)
   Plant age: less than 1 year old
   Supporting material: planter boxes filled with soil (with thickness of 22 cm)
   Air cavity between façade and planter boxes: 4 cm
   Building material façade: plywood
   Location: rural area

Experimental description:
An experimental procedure was addressed in order to measure surface temperature, air temperature and wind velocity applicable for each greenery system (figure 5.4.3). Measurements were carried out on both bare and greened walls. Measurements are done on the green layer and on a bare façade next to it, to compare for each site the influence of the greening systems. For the living wall system no bare façade was available to compare. Measurements are taken at the same height of 1,50 m and in a surface area of 1 m^2. Measuring points, for air temperature and wind speed, are chosen at fixed distances – 1 m in front of the greened façade, 10 cm in front of the bare and the greened façade, in the middle of the plant layer (foliage) and in the air cavity – for all the green systems; surface temperature was measured on surfaces covered with leaves, on bare surfaces and on outer and inner leaves. For the living wall system additional measurements are done behind the leaves (planter boxes) as well. In total 10 measurements are taken per site in the period of September till end of October. For each measurement 10 samples are taken and thus makes a total of 100 samples for each analyzed system; data logging per measurement take place every 15 sec.

The instrumentation used for the field measurements includes an infrared thermometer and a combined wind velocity and air temperature data acquisition device. For convenience and mobility during carrying out measurements, portable measuring devices have been used for (surface and air) temperature and wind velocity measurements. The wind velocity and air temperature measurements are done with a Testo handheld hot wire probe. Surface temperatures (spot measurements) were determined using an infrared thermometer with a temperature range of -50 to 650 °C to measure the blackbody radiation emitted from selected objects. Selected objects that are measured are: leaf surface, wall surface and planter boxes of the LWS façade.

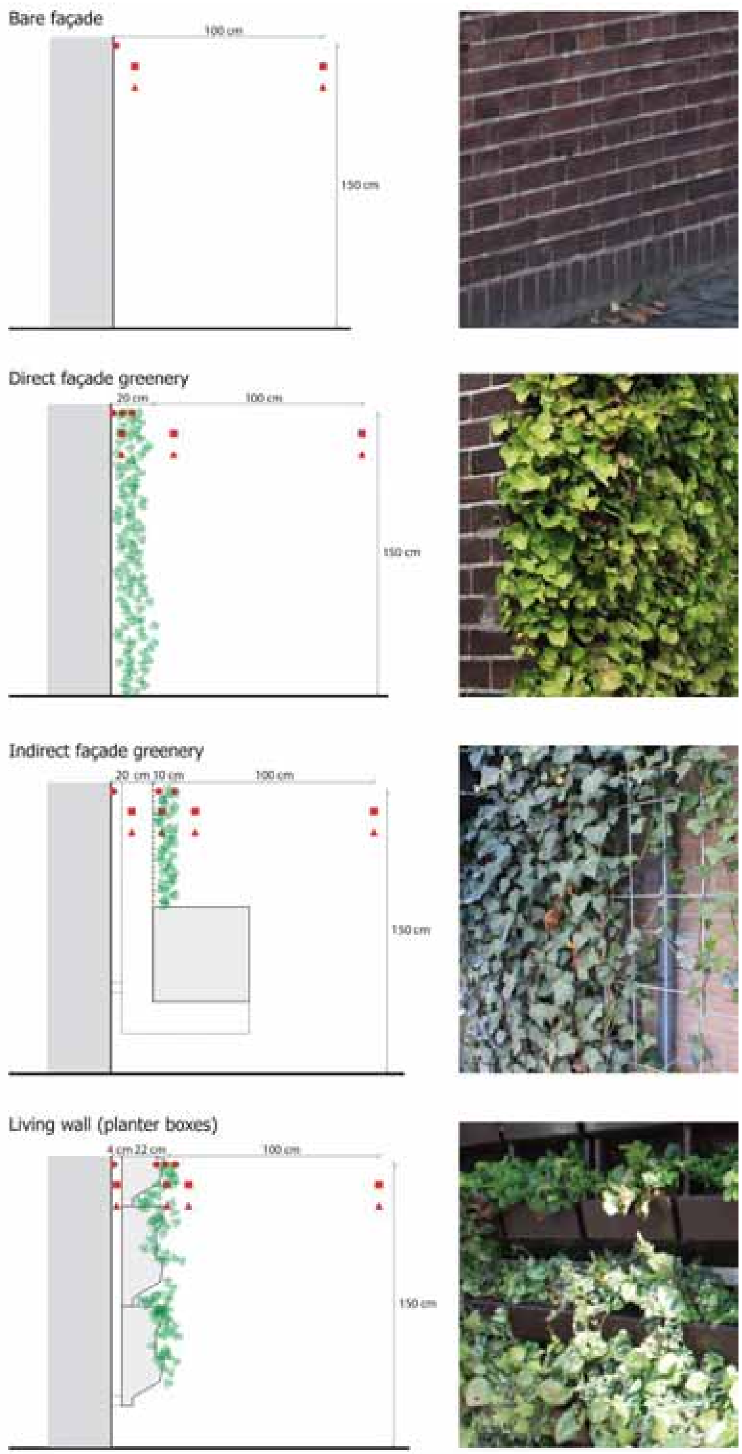

Figure 5.4.3 Measuring points for the vertical green systems analyzed.

Data processing

In order to evaluate the obtained data, a block design was used. Blocking enables to arrange the data into categories: wind speed and temperature. The category temperature is built up by dividing the data in blocks namely: highest temperature, average temperature, lowest temperature. For the category wind speed the obtained blocks are: high wind speed, average wind speed, low wind speed. The values within the blocks are presented by taking the 1m measurements for air temperature and wind speed as starting point for a percentage comparison.

Results and discussion

Air and surface temperature measurements

For all the greening systems analyzed compared with the bare walls, starting from 1 m until 10 cm in front of the façades, no air temperature difference was recorded. The temperature profile for the direct greening situation shows a tendency to follow the temperature profile of the bare wall next to the green layer (figure 5.4.4, table 5.4.1). A small temperature difference ($\Delta T_{surface}$ = 1.2 °C) is noticed only for the surface temperature of the bare wall compared with the direct green situation. For the indirect climber situation the tendency of the temperature profile is similar of the direct climber situation (figure 5.4.5, table 5.4.2). The difference of the surface temperatures (bare-indirect green) is $\Delta T_{surface}$ = 2.7 °C. For the living wall system no data was available for a bare wall situation. An hypothetical line was drawn on the basis of the measurements done on the other locations to compare the temperature profile. The surface temperature difference between the hypothetical bare wall profile and the LWS façade is $\Delta T_{surface}$ = 5 °C. The air temperature, starting from 10 cm in front of the LWS till the air cavity behind it, increases with 1.1 °C (see figure 5.4.6 and table 5.4.3). In the case of the living wall system, compared with the other greening systems, a higher temperature different was found; it is likely that this temperature difference is caused by 100% reduction of the sun radiation due to the materials involved.

The temperature profiles found for the investigated façades show no notable differences between the bare and the greened façades. This is probably due to the fact that the measurements are carried out in autumn without direct sun and with exterior surface temperatures lower than 18 °C. A research, carried out by Bartfelder and Köhler (1987) in Berlin (Germany) during summer, shows a similar trend for low surface temperatures (respectively 16.7 °C for the bare façade and 16.3 °C behind the foliage). Differently, for warmer temperatures, it was found 31.0 °C for the bare façade and 25.2 °C for the greened façade; which indicates that vegetation has an influence on the building skin depending on the environmental conditions. Wong et al. (2009) show a 4.36 °C reduction in the average temperature on the wall surface on 21 June 2008 in Singapore for an indirect climber system compared with a bare wall. Besides this a temperature reduction behind a LWS filled with soil substrate compared to the bare wall ranges from about 2 °C at night and up to 9 °C in the afternoon. Considering the data shown by the researches, further measurements are recommended for the four seasons to get insight in the possible temperature decrease or increase thanks to a vertical greening system.

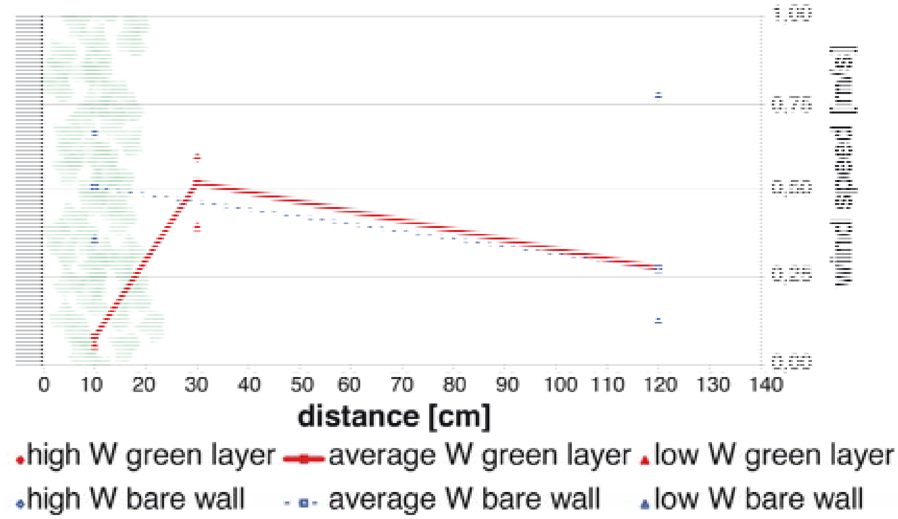

Figure 5.4.4a Wind speed profile given for a direct façade greenery system based on Hedera Helix.

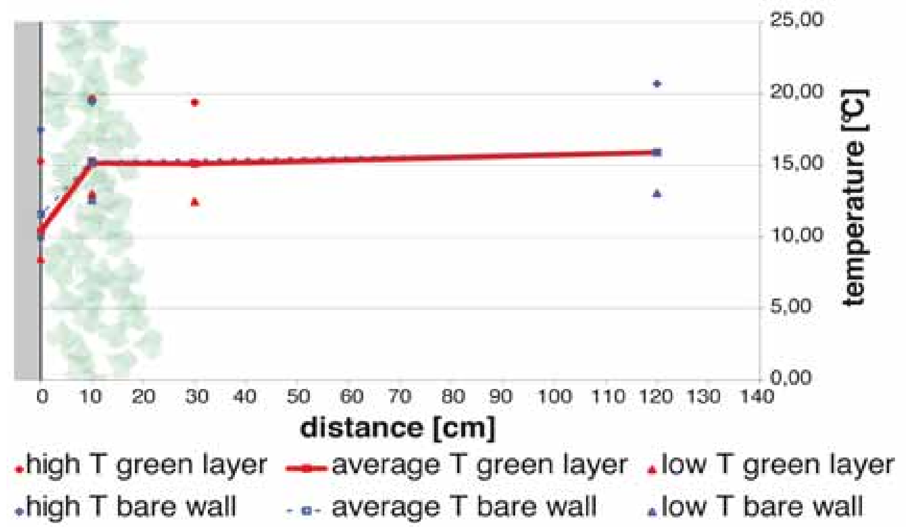

Figure 5.4.4b Wind speed profile given for a direct façade greenery system based on Hedera Helix.

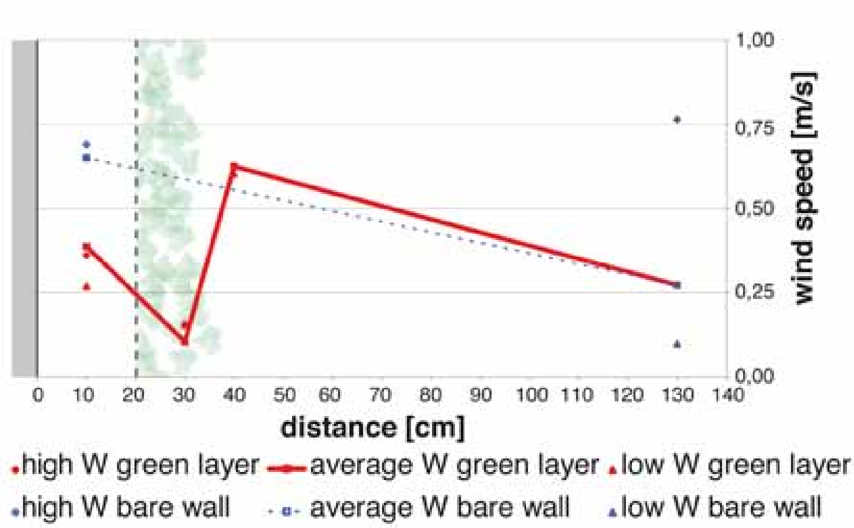

Figure 5.4.5a Wind speed profile given for an indirect façade greenery system based on Hedera Helix.

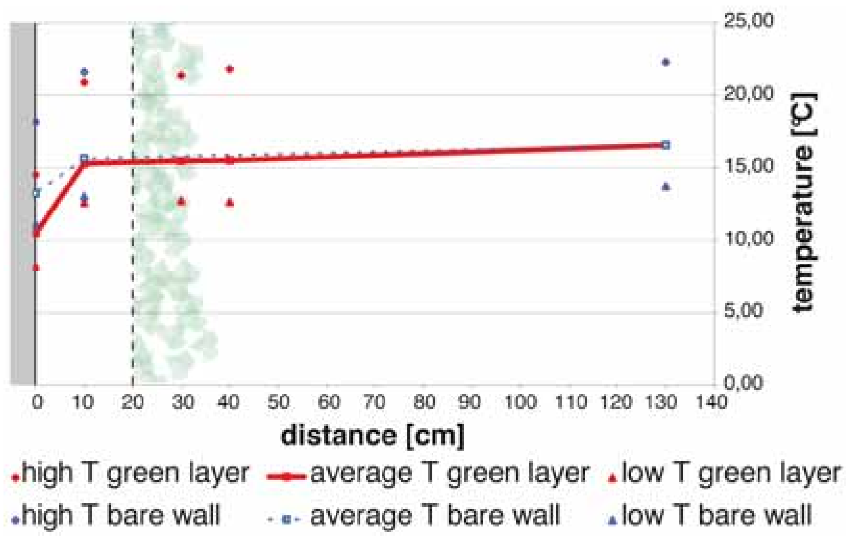

Figure 5.4.5b Temperature profile given for an indirect façade greenery system based on Hedera Helix.

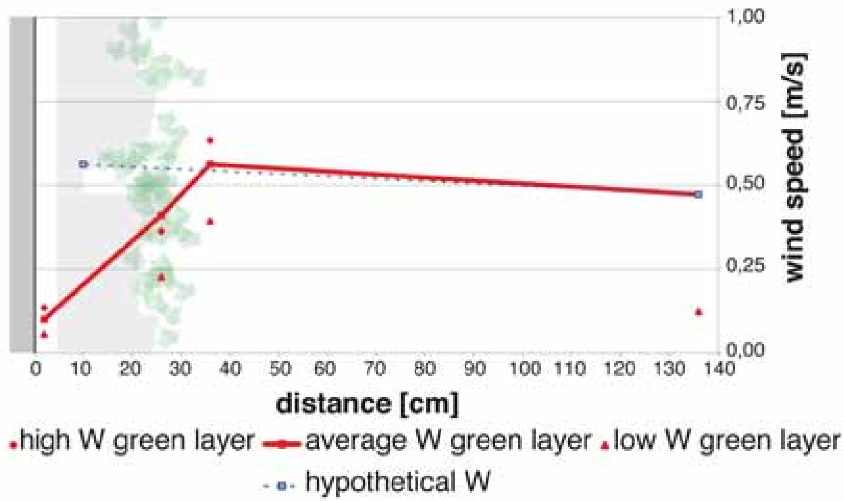

Figure 5.4.6a Wind speed profile given for an living wall system based on planter boxes.

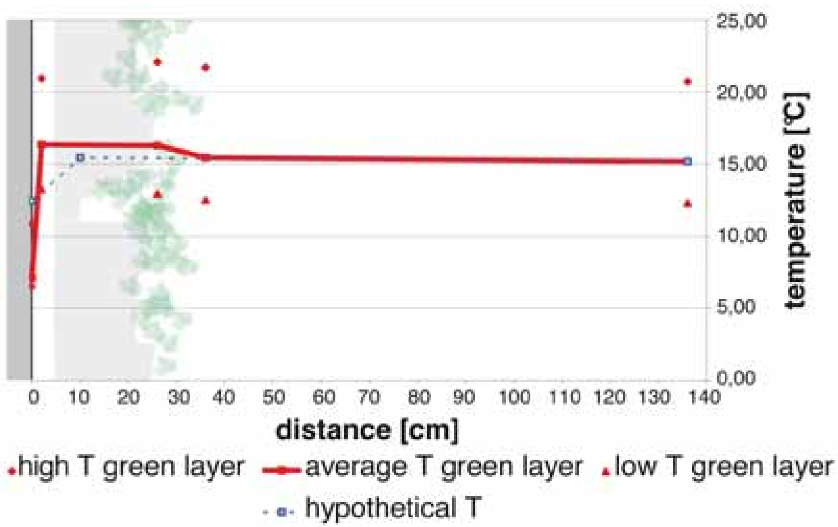

Figure 5.4.6b Temperature profile given for an living wall system based on planter boxes.

Table 5.4.1 Direct façade greenery, temperature and wind speed profiles.

	highest T [°C]		average T [°C]		lowest T [°C]	
Bare wall 1 m air temperature	20,69	***100%***	15,89	***100%***	13,05	***100%***
Bare wall 0,1 m air temperature	19,45	94%	15,27	96%	12,58	96%
Bare wall surface temperature	17,46	84%	11,59	73%	10,02	77%
Greened wall 1 m air temperature	20,69	***100%***	15,89	***100%***	13,05	***100%***
Greened wall 0,1 m air temperature	19,39	94%	15,10	95%	12,46	95%
Greened wall outer leaf surface temperature	17,39	84%	11,06	70%	8,56	66%
Greened wall inner leaf surface temperature	16,27	79%	10,61	67%	7,23	55%
Greened wall inner leaf air temperature	19,65	95%	15,15	95%	12,98	99%
Greened wall surface temperature	15,28	74%	10,39	65%	8,44	65%

	highest W [m/s]		average W [m/s]		lowest W [m/s]	
Bare wall 1 m wind speed	0,77	***100%***	0,28	***100%***	0,13	***100%***
Bare wall 0,1 m wind speed	0,67	86%	0,51	184%	0,36	287%
Greened wall 1 m wind speed	0,77	***100%***	0,28	***100%***	0,13	***100%***
Greened wall 0,1 m wind speed	0,60	77%	0,52	189%	0,40	315%
Greened wall inner leaf wind speed	0,08	11%	0,08	29%	0,06	45%

Table 5.4.2 Indirect façade greenery, temperature and wind speed.

	highest T [°C]		average T [°C]		lowest T [°C]	
Bare-greened wall 1 m air temperature	22,29	***100%***	16,55	***100%***	13,73	***100%***
Bare wall 0,1 m air temperature	21,60	97%	15,63	95%	13,02	95%
Bare wall surface temperature	18,16	81%	13,23	80%	11,11	81%
Greened wall 0,1 m air temperature	21,80	98%	15,50	94%	12,63	92%
Greened wall outer leaf surface temperature	18,89	85%	13,04	79%	10,77	78%
Greened wall inner leaf surface temperature	17,56	79%	12,24	74%	9,72	71%
Greened wall inner leaf air temperature	21,36	0,96	15,46	94%	12,72	93%
Greened wall air cavity air temperature	20,90	94%	15,29	92%	12,59	92%
Greened wall surface temperature	14,52	65%	10,50	63%	8,17	59%

	highest W [m/s]		average W [m/s]		lowest W [m/s]	
Bare wall 1 m wind speed	0,76	***100%***	0,27	***100%***	0,10	***100%***
Bare wall 0,1 m wind speed	0,69	90%	0,65	239%	0,65	665%
Greened wall 0,1 m wind speed	0,62	81%	0,62	230%	0,60	617%
Greened wall inner leaf wind speed	0,16	20%	0,10	38%	0,15	158%
Greened wall air cavity wind speed	0,36	47%	0,39	142%	0,27	274%

Table 5.4.3 Living wall system, temperature and wind speed.

	highest T [°C]		average T [°C]		lowest T [°C]	
Greened wall 1 m air temperature	20,68	***100%***	15,15	***100%***	12,28	***100%***
Greened wall 0,1 m air temperature	21,67	105%	15,42	102%	12,47	102%
Greened wall outer leaf surface temperature	17,18	83%	10,95	72%	7,55	62%
Greened wall material surface temperature	14,89	72%	9,18	61%	6,86	56%
Greened wall inner leaf air temperature	22,05	107%	16,27	107%	12,91	105%
Greened wall air cavity air temperature	20,91	101%	16,33	108%	13,23	108%
Greened wall surface temperature	10,83	52%	7,10	47%	6,58	54%

	highest W [m/s]		average W [m/s]		lowest W [m/s]	
Greened wall 1 m wind speed	2,33	***100%***	0,47	***100%***	0,12	***100%***
Greened wall 0,1 m wind speed	0,63	27%	0,56	119%	0,39	319%
Greened wall inner leaf wind speed	0,36	15%	0,41	87%	0,23	184%
Greened wall air cavity wind speed	0,13	6%	0,10	21%	0,06	45%

Wind speed measurements

The wind profile for direct greening concept shows a decrease in wind velocity (ΔW = 0.43 m/s) inside the foliage compared with 10 cm in front of the bare façade. The wind velocity inside the foliage has the tendency to be nearly zero (figure 4). For the indirect greening system (figure 5) the wind velocity decreases inside the foliage as well (ΔW = 0.55 m/s); however it increases inside the air cavity (ΔW = 0.29 m/s). The wind velocity profile for the living wall system shows a decrease from 0.56 m/s to 0.10 m/s (ΔW = 0.46 m/s) starting from 10 cm in front of the façade to the air cavity (based on a hypothetical wind velocity for a bare wall situation), as shown in figure 5.4.6.

The wind velocity profiles show that the foliage allows obtaining a decrease in wind velocity. The increase of the wind velocity inside the air cavity (20 cm) for the indirect climber system, which was not noticed inside the air cavity (4 cm) of the LWS façade, can be clarified through the relative thickness of the air cavity between the foliage and façade or the porosity (thickness of the foliage) of the climbing plant. Besides that living wall systems are in general made out of several dense layers (felt, plastics, soil, etc.) so there is less effect of wind penetration, as can happen for dense foliage.

The results show the potential of vertical greening layers on reducing the wind velocity around building façades. The type of greening system (direct, indirect or LWS) and its properties (foliage, porosity, materials used, etc.) influences this effect. Since the thermal transmittance (and thus insulation properties as well) of a building is among other things dependant and affected by the wind velocity that passes the surface of the building, a green façade can enhance the thermal properties of a façade.
The current standardisation for the thermal transmittance of a construction (NEN-EN-ISO 6946:2008) assumes a wind speed of 4.0 m/s year round at the exterior

surface for calculating the heat transfer coefficient (exterior surface resistance R_e = 0.04 m²K/W). For interior surfaces the standardisation applies 0.2 m/s along the wall surface (interior surface resistance R_i = 0.13 m²K/W).

The thermal resistance of a construction is determined according to: $\sum R_e + R_T + R_i$

with R_T as the sum of the thermal resistances of individual layers (materials) of the system.
For the direct greened façade a decrease in the wind speed was observed inside the foliage, from the measurements the average value of 0.08 m/s was found (90% of the 100 data points were lower than 0.2 m/s), see table 1. For the living wall system (table 5.4.3) the average value of the wind speed inside the air cavity was 0.1 m/s (85% of the 100 data points were lower than 0.2 m/s).

When the wind speed outside is lower than 0.2 m/s (standard interior wind speed for calculation), due to the contribution of the foliage or the other layers involved (LWS), R_e can be equalized to R_i. In this way the benefit on thermal resistance of the construction can be quantified by an increase of 0.09 m²K/W. This implies energy savings for building envelopes in warmer and colder climates; in addition to increasing the thermal resistance also lower surface temperatures (shaded by foliage) have an effect on the cooling capacity of buildings, especially in warmer climates.
Thermal resistance without a green layer:

$$\sum R_e + R_T + R_i = 0.04 + R_T + 0.13 = 0.17 + R_T \left[m^2K/W \right]$$

with a direct greening system:

$$\sum R_e + R_T + R_i = 0.13 + R_T + 0.13 = 0.26 + R_T \left[m^2K/W \right]$$

and with a LWS (additional thermal properties of the layers involved):

$$\sum R_e + R_{LWS} + R_T + R_i = 0.13 + R_{LWS} + R_T + 0.13 = 0.26 + R_{LWS} + R_T \left[m^2K/W \right]$$

For the indirect greening system (table 5.4.2) the values obtained are higher, with an average wind speed of 0.39 m/s (60% of the 100 data points were lower than 0.2 m/s); so for this situation it is not valid to equate R_e with R_i. The indirect green façade system studied in this research contains an air cavity of 20 cm. It was noticed that the wind speed inside this cavity (0.39 m/s) increases again, after the foliage reduction till 0.10 m/s. Additional measurements are recommended to evaluate the influence of the air cavity thickness on lowering the wind velocity.

The results of this research shows that an air cavity of 20 cm doesn't act like a stagnant air layer, because of the higher wind speed measured; therefore it seems useful to reduce the distance between foliage and façade to obtain optimal thermal properties. Basing on the results of the wind speed inside the air cavity of the LWS (40 mm), it can be noticed that also for greening systems an optimal air cavity thickness exist (around 40-60 mm), according to building physic regulations (a 50 mm air cavity acts like 0.5 mm of insulation material).

The reduction of the wind velocity around the building envelope due to the use of a green skin has a contribution to the thermal properties of that envelope and could lead to energy savings for cooling and heating. Considering the thermal properties of the building envelope, the influence of a green layer can be higher for constructions that need to be retrofitted (low thermal resistance). However, according to the building regulation standards, any of the green systems analyzed could not replace the insulation material to fulfil the thermal resistance required.

A greening system can be used in combination with (external) insulation material especially for retrofitting of existing constructions with energy efficiency problems.
The benefits of vertical greening concepts discussed in this paper for the thermal behaviour have to be added to the multi-functionality of vegetation for the urban environment, with respect to the increase in biodiversity, mitigation of urban heat island effect, reduction of air pollution, production of biomass and the social and psychological well being of city dwellers.

Conclusions
Since the research was focussed on quantifying the wind velocity profile inside and behind the greening systems and in the possible effect on the thermal resistance; the main conclusions that can be drawn from the presented results are the follows:

- No difference was found in the air temperature and wind profiles starting from 1 m in front of the façades till inside the foliage.
- The investigated vertical greening systems are effective natural sunscreens, due to a reduction of the surface temperatures behind the green layer compared to the bare façades.
- Inside the foliage of the direct and indirect systems and inside the air cavity of the LWS a low (respectively 0.08 m/s and 0.1 m/s) wind velocity was measured.
- The higher wind velocity found inside the air cavity of 20 cm thickness of the indirect greening system demonstrates that it is also possible to speak about an optimal air cavity thickness for greening systems (around 40-60 mm).
- Due to the reduction of wind velocity measured (<0.2 m/s) the exterior surface resistance (R_e) could be equalized to the interior surface resistance (R_i). This affects the total thermal resistance of the façade which results in energy savings.

The direct greening system and the living wall system based on planter boxes are the most effective wind barriers, the reduction of the wind velocity affects the thermal resistance of the building envelope and thus his efficiency. The indirect greening system analyzed doesn't affect the thermal resistance due to the thickness of the air cavity; it is likely that the same system with an air cavity of 40-60 mm could work as an stagnant air layer. The system with the major impact on the thermal resistance is the living wall system based on planter boxes, thanks to the "extra" created air cavity and to the thermal resistance of the other material

layers involved (HDPE and soil) that can be added to the benefit of the wind velocity reduction due to the foliage. It is also possible to assume that, from a functional point of view, most of the living walls systems, compared to green façades, demand a more complex design, which must consider a major number of variables (several layers are involved, supporting materials, control of water and nutrients, etc.), on top of which they are often very expensive, energy consuming and difficult to maintain.
This study gives the possibility to calculate the energy saving for heating and cooling with several vertical greening systems, with similar characteristics to the systems as analyzed in this study.

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5.5 Experimental approach; quantifying thermal behaviour of vertical greening concepts

In order to estimate and predict how a vertical green layer will influence the thermal behaviour of a façade element and thus its interaction with the exterior and interior climate, temperature measurements are needed under different environmental conditions (summer, winter). Further each vertical greening system could have a different effect on the temperature gradient. An experimental set-up in a laboratory is advisable to have the possibility for replication of the measurements and to compare between the measurements. Another important reason to make use of laboratory conditions is among other things, a lack of green façades in the field and differences between locations with respect to façade orientation and environmental parameters. For this reason an experimental set-up was designed and built to quantify the differences between different vertical greening principles. The presented experimental set-up describes a procedure for measurements of steady-state (stationary condition) heat transfer through a typical cavity wall covered with different vertical greening systems. The reference cavity wall is consisting of an inner wall of 100 mm (limestone), mineral insulation material of 100 mm (Rockwool), air cavity of 50 mm and an outer wall of 100 mm (brick), with a façade surface of $1m^2$ (width and height are each 1 m).

The designed apparatus (climate chambers) is intended to reproduce different boundary conditions of a specimen between two environments, called indoor and outdoor climate. In the middle of the chamber a cavity wall was constructed (as reference material and to test the influence of vertical green on the multilayered system). The cavity wall is therefore also acting as a sample holder for vertical green cladding systems and divides the box automatically into two chambers; an "outside climate chamber" and an "inside climate chamber" with no direct interaction between them.
The designed apparatus used in this experiment was designed and constructed based on NEN-EN 1934. The standard requires a "hot" chamber on one side of the tested specimen and a heat sink in the form of a "cold" chamber in which environmental conditions are imposed. The constructed box (the hot and cold chambers) is insulated from its surroundings using 200 mm (2 layers overlapped of 100 mm) of EPS insulation material, with a conductivity of 0.036 W/m.K. The 2 layers of EPS are glued together and glued to plywood sheathing of 18 mm. In the "hot" chamber extra insulation material was attached to the EPS in order to minimize heat losses. For this application ISOBOOSTER-T1 sheets were used of 30 mm thickness with a U - value of 0.42 $W/m^2 \cdot K$.

Details of the designed climate chamber

Since the standard (NEN-EN 1934) describes (as guide) the basic elements for designing a "hot" and "cold" chamber, no size dimensions are given to construct the experimental set-up. However the bare wall (insulated cavity wall) as earlier described has a dimension of $1m^2$, most of the available living wall systems consist of modular panels with size dimensions varying per company. Depending to their size one, two or more panels can be used to cover 1 m^2 façade. For the direct and indirect greening systems sizes are less important, because they can be easily adapted to a size needed for the experimental set-up. For practical reasons (placing the panels, thermocouples, etc.) and to have some size tolerance for placement of living wall systems, the following dimensions are used inside the climate chambers (figures 5.19a and b):

<u>The inside dimensions of the climate chambers are the same, and they have the following dimensions:</u>

- length L = 1100 mm
- width w = 1400 mm
- height H = 1400 mm

After defining the inside dimensions of the climate chambers, given the thickness of the insulation material to separate the chambers from its surrounding, the following outside dimensions for the designed apparatus (including the chambers) are found (figures 5.19a and b):

<u>The outside dimensions of the designed apparatus:</u>

- length L = 3000 mm
- width w = 1800 mm
- height H = 1800 mm

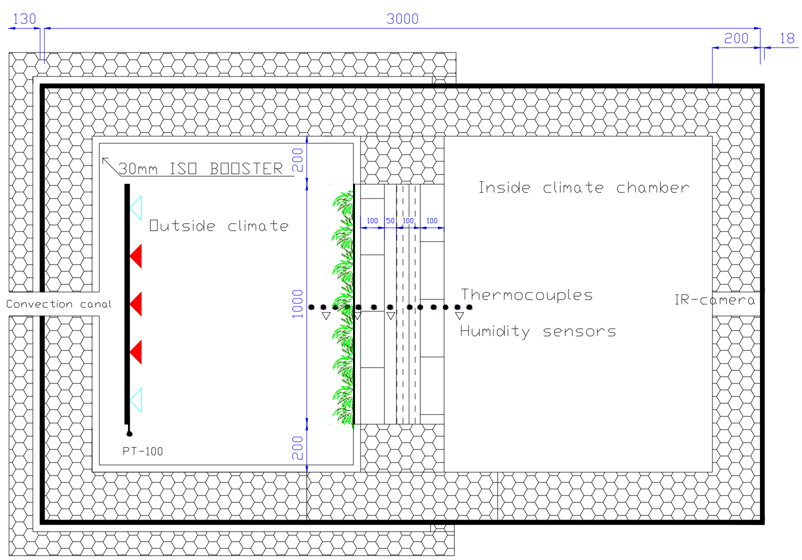

Figure 5.19a Top view of the designed climate chambers with dimensions and positions of the thermocouples and humidity sensors. Dimensions are in mm.

In order to minimize the heat loss through the walls of the outside climate chamber (chamber where heat and cold is generated), an extra insulation layer of 100 mm EPS with an air cavity of 30 mm was constructed at the outside of the box, around the outside climate chamber (right side in figure 5.19a and b). This extra layer serves as a guard by keeping the temperature of the air cavity the same temperature as the outside climate chamber. The guard section ensures that the lateral heat flow rate from the outside chamber to the guard section is (nearly) zero to avoid energy losses. On this way an adiabatic environment is created inside the climate chamber.

A digital temperature controller and convective heater (hot gun) as well as infrared radiation bulbs maintain the box temperature as close as possible to environmental conditions. An automatic data collection system is used in this experiment, so that tests can be conducted over a long period of time (if needed) to assure steady-state conditions and to determine reproducibility of the laboratory measurements.

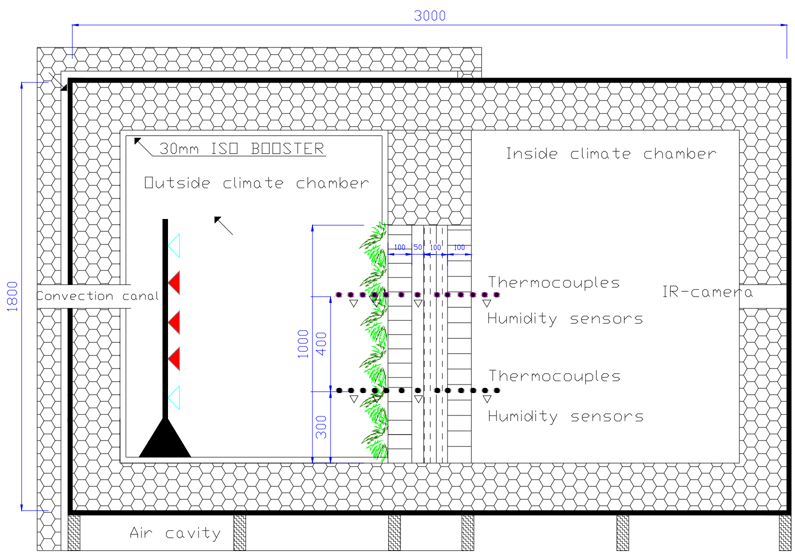

Figure 5.19b Cross section of the designed climate chambers with dimensions and positions of the thermocouples and humidity sensors. Dimensions are in mm.

To ensure that the heat transfer only via the bare wall occurs, the surrounding structure of the designed apparatus and the enclosure around the bare wall must have a higher thermal resistance than the bare wall itself. Therefore several thermal transfer possibilities are calculated (*R-value*) and checked (infrared camera) to ensure that there are no thermal weak spots.

The calculated *R-value*s in figure 5.19c, consist of the thermal resistance of EPS insulation plus the additional ISOBOOSTER insulation layer. The critical paths of heat transfer inside the designed apparatus are:

1. Surrounding area of the designed apparatus (200 mm EPS + 30 mm Isobooster).
2. Along the bottom (edge; between the chambers) of the bare wall (350 mm EPS + 30 mm Isobooster).
3. The bare wall (100 mm masonry, 50 mm air cavity, 100 mm mineral wool and 100 mm limestone).
4. Over the top (edge; between the chambers) of the bare wall (350 mm EPS + 30 mm Isobooster).

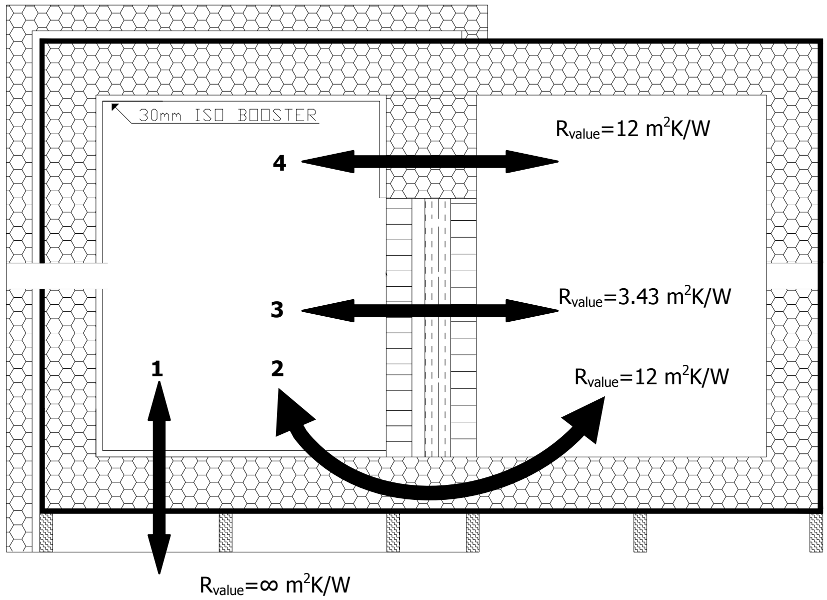

Figure 5.19c Possible critical paths for heat transfer, since the R-value of the bare wall (3) is significant lower than the R-values calculated for the edges (2 and 4) and the surrounding envelope (1), the heat flow will follow the path of the least resistance.

Data logging and processing

Inside the designed climate chambers, at different locations, several sensors are placed to measure the temperatures and humidity levels through the bare wall and vertical greening system. Temperature measurements were done using thermocouples of type T (Cu-Ni). The relative humidity (RH) inside the climate chambers was measured by Honeywell hygrometers with a thermoset polymer capacitive sensing element. The data was collected and recorded on a data logger with a frequency of acquisition of 60 scans per hour. The total system was controlled by a personal computer.

Number of sensors used in the climate chambers:

- 30 Air and surface temperature sensors placed at two levels (x-axis).
- 10 Humidity sensors Honeywell placed at two levels (x-axis).

In order to study the effect of convection (warm air) and radiation (sun) on the heat transfer through a greened wall, both are tested separately. The sensors used during the experiments related to the climate chambers are indicated in figures 5.19a and b. The temperature of the extra air cavity was controlled via a PT100 in combination with an ENDA ET1411 digital thermostat temperature controller (connected to a solid state relay). The box tightness (thermal leakage) inside and outside the box was determined by the use of an infrared camera (FLIR A320).

Control system convection and radiation

The convection heating system in the outside climate chamber consists of a hot gun in an insulated enclosure. The maximum power output of the hot gun is 1500 W (T_{Imax} 300 °C, T_{IImax} 500 °C). The temperature in the outside climate chamber is controlled via a PT100 in combination with an ENDA ET1411 digital thermostat temperature controller (connected to a solid state relay).

The radiation power system in the outside climate chamber consists of 9 PAR38 light bulbs which are used to supply radiation energy to the bare wall or vertical green system.

- Infrared radiation power: 9 bulbs PAR 38 of 100W (red)
- Plant reflector lamp: Halogen 75W E27 240V PAR30 (purple)

Data acquisition and thermocouple measurements

For the thermal data acquisition 4 calibrated Advantech 4781 USB modules are used for the thermocouple readings. The data acquisition for the humidity sensors was done by a multifunctional DAQ NI USB-6211 module. All used thermocouples are of type T with a diameter of 0.25 mm. Near the PT100 a thermocouple of type T was placed to verify the temperature inside the chambers. Each thermocouple reading consists of 2 measurements on the same y-axis with a distance of 400 mm, see figure 5.19b.

Figure 5.20 Left photograph; building of the bare wall as used for the measurements. Right photograph; the bare wall as a package of 1 m^2 ready for placement inside the designed apparatus.

Figure 5.21 Finishing the outer masonry it is also possible to see the wires for thermocouples and humidity sensors as placed inside the bare wall.

Figure 5.22 Cross section of the different layers of the bare wall; from left to right: limestone, mineral wool, air cavity and the masonry of clay.

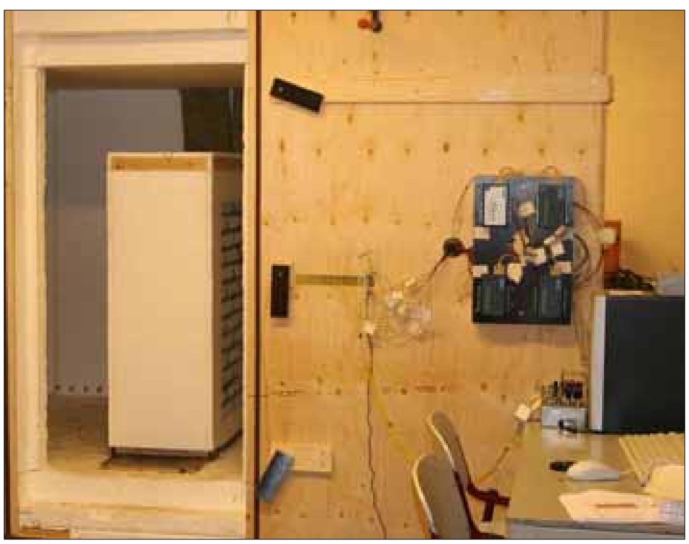

Figure 5.23 The bare wall as placed inside the designed apparatus, dividing the box into two chambers, the outside chamber (right handed) and the inside chamber (left handed). On this way two different climates can be achieved and simulated.

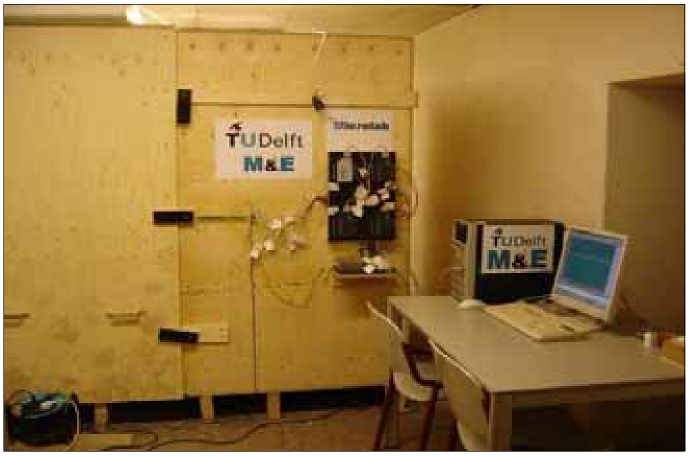

Figure 5.24 The designed apparatus closed and ready to simulate a measurement. Several digital data loggers and a personal computer are shown to fulfil the experiments.

Figure 5.25 The climate chamber where the heating or cooling energy is generated, is protected against the influence of the environment with an extra guard (cavity with the same temperature as inside the climate chamber to avoid energy losses). On this way an adiabatic environment is created.

Figure 5.26 Panel with infrared bulbs (red) to simulate radiation and growing bulbs (purple) to maintain an "optimal" condition for the plants (when the box is closed no light is available for photosynthesis, since a greening system is roughly two weeks inside the box artificial light is necessary to keep the plants alive during the measuring period.

According to the different greening types available on the market, different systems are tested in the experimental set-up. The systems that are tested can be found in table 5.13.

Table 5.13 Vertical green classification and the concepts as tested in the designed apparatus.

Green façade classification	**Vertical green types**				
	Fixation principles against the façade	**Characteristic features**	**Plant types and systems**[20]		**Testing in climate chambers**
Rooted in subsoil	**Direct** *(uses the façade as guide to grow upwards)*	Self climbing climbers	Aerial roots		***Paragraph 5.5.1***
			Suckers		
	Indirect *(distance between climbing plant and façade via an supporting system used as guide to grow upwards)*	Self climbing climbers with supporting system	Aerial roots		***Paragraph 5.5.2***
			Suckers		
		Climbers with supporting system	Twining climbers		
			Tendril climbers		
			Scrambling climbers		
Not rooted in subsoil	**Direct** *(uses the façade as guide to grow upwards or to root in)*	Self climbing climbers	Aerial roots		
			Suckers		
		Natural wall vegetation	Herbaceous plants		
			Woody plants		
		Artificial wall vegetation (concrete)	Herbaceous plants		
	Indirect *(distance between climbing plant and façade via an supporting system used as guide to grow upwards)*	Climbers with supporting system	Twining climbers		
			Tendril climbers		
			Scrambling climbers		
		Living wall systems (LWS)	*Greenwave*	Greenwave systems	***Paragraph 5.5.3***
			Vertical gardens	Vertical garden systems	
			Wallflore per	Cultilene	
			Wallflore soft	Cultilene	***Paragraph 5.5.4***
			Wallplanter	Mobilane	
			Livepanel	Mobilane	
			Fytowall	The vertical green company	***Paragraph 5.5.5***
			VGM green wall	Elmich	
			Living wall systems	ELT easy green	
			Wonderwall	Copijn	***Paragraph 5.5.6***
			Le Mur Végétal	Patrick Blanck	
			Limeparts	Limeparts Architects	
			"Gevelbegroeiing" systeem	Optigroen Dak en Gevelbegroeiing	

[20] Due to the rapid development of living wall systems at the moment by companies, the living wall systems named in table 5.13, gives only an impression of the variety within this market.

5.5.1 Measuring *Hedera helix* (direct façade greening principle)

Figure 5.27 Roughly 1 m² of Hedera helix placed in a container filled with soil to ensure the plants vitality during the measurements inside the box.

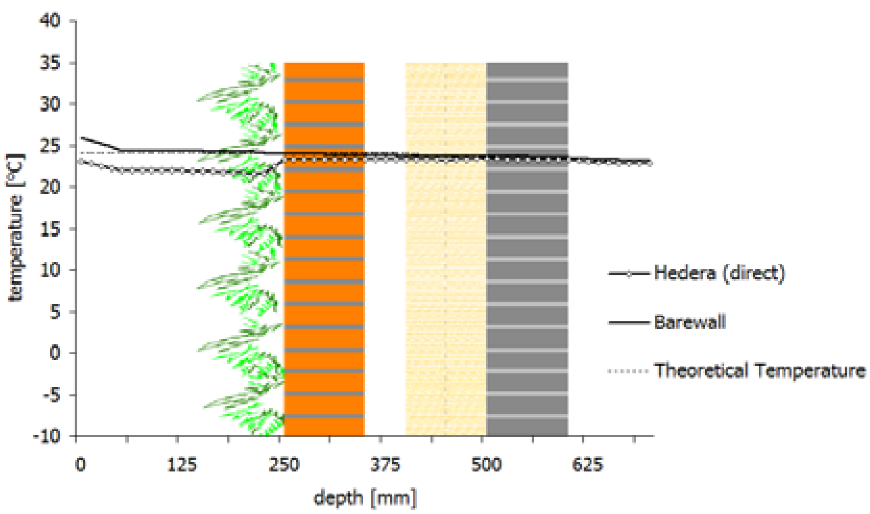

Figure 5.28 Temperature development at the beginning of the summer measurement, for a bare wall compared with a direct greening principle; t=0 hour.

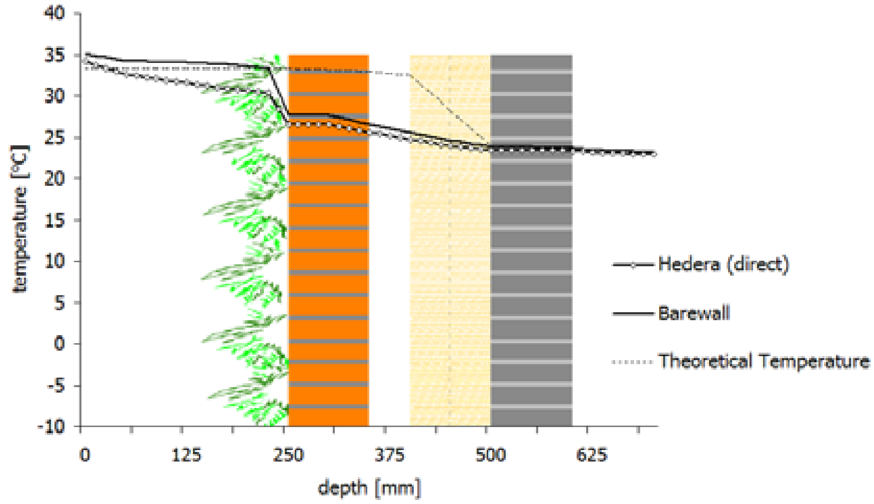

Figure 5.29 Temperature development after 2 hours of heating (35 °C), for a bare wall compared with a direct greening principle; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

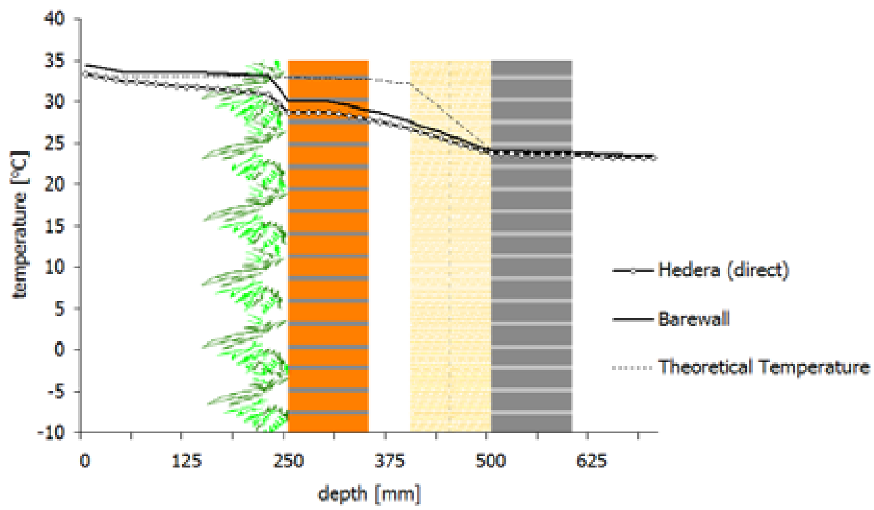

Figure 5.30 Temperature development after 4 hours of heating (35 °C), for a bare wall compared with a direct greening principle; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

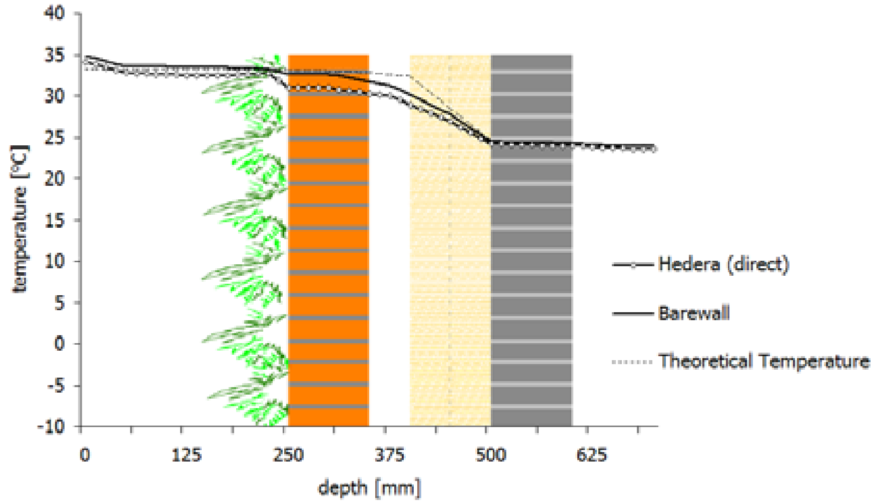

Figure 5.31 Temperature development after 8 hours of heating (35 °C), for a bare wall compared with a direct greening principle; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

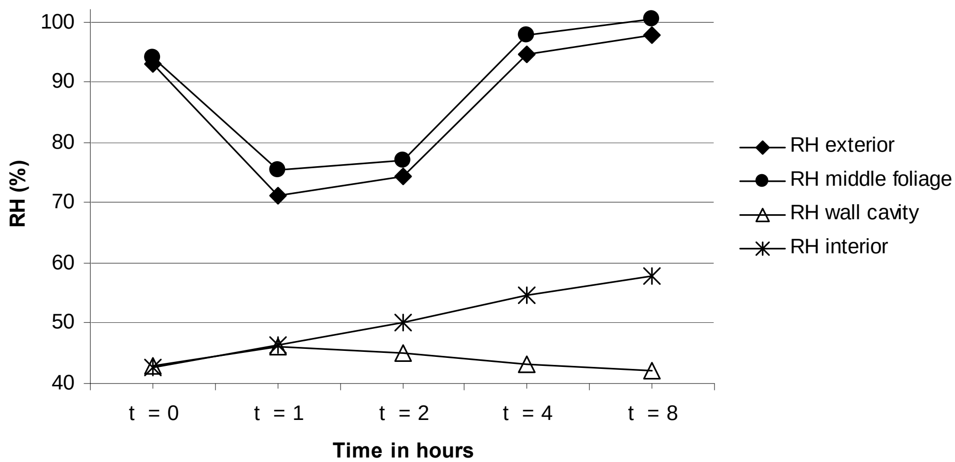

Figure 5.32 Humidity development over different time steps, for a bare wall compared with a direct greening principle, given for the summer measurement.

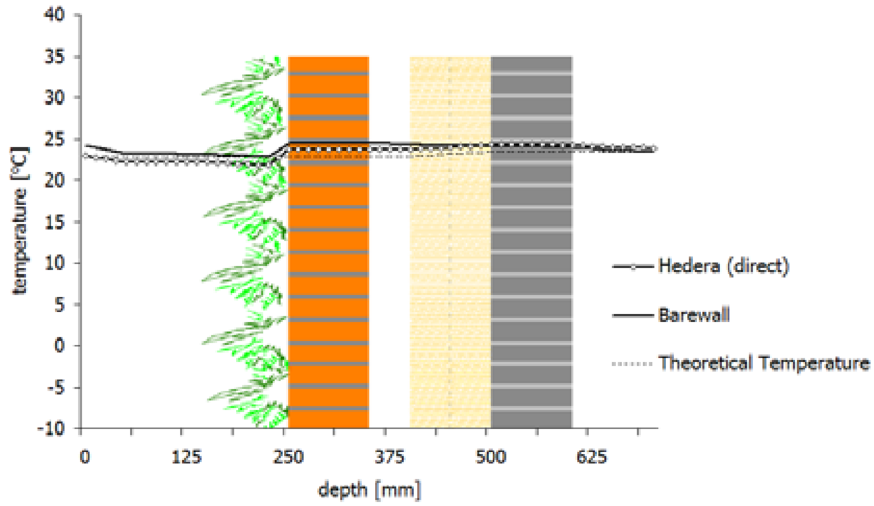

Figure 5.33 Temperature development at the beginning of the winter measurement, for a bare wall compared with a direct greening principle; t=0 hour.

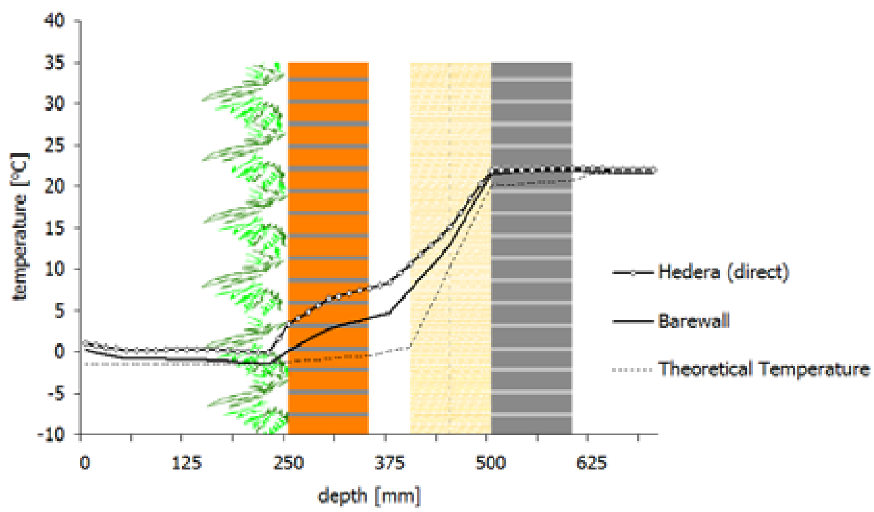

Figure 5.34 Temperature development after 24 hours of cooling, for a bare wall compared with a direct greening principle; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

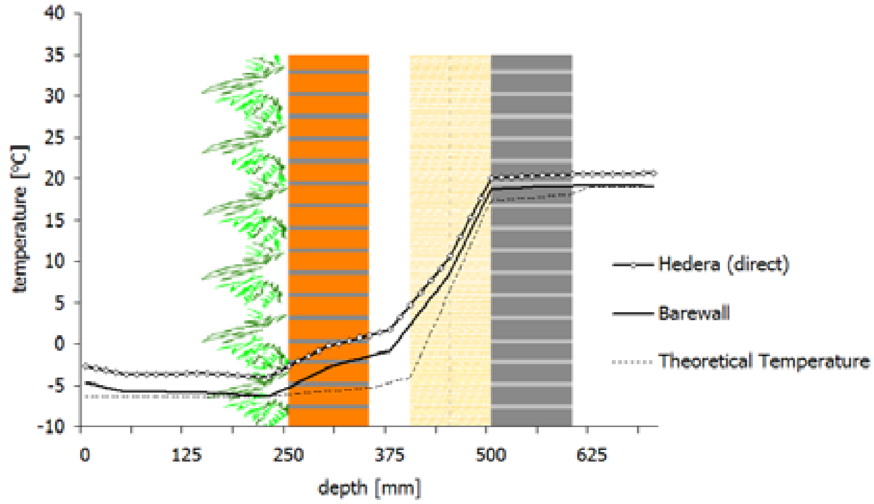

Figure 5.35 Temperature development after 48 hours of cooling, for a bare wall compared with a direct greening principle; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

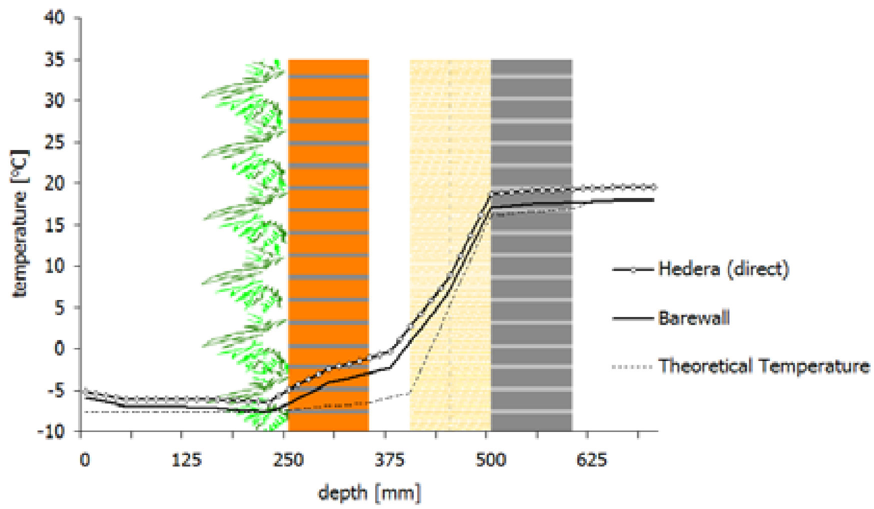

Figure 5.36 Temperature development after 72 hours of cooling, for a bare wall compared with a direct greening principle; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

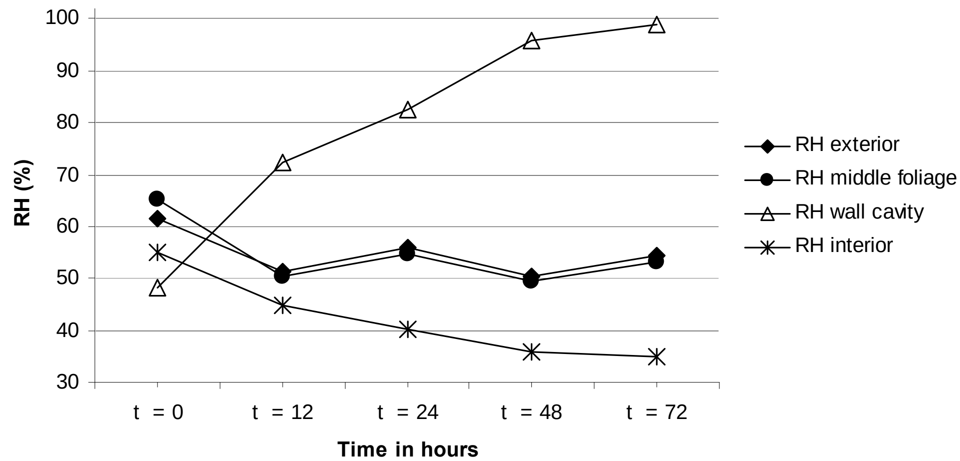

Figure 5.37 Humidity development over different time steps, for a bare wall compared with a direct greening principle, given for the winter measurement.

Table 5.14 Summarized data obtained by the thermocouples positioned through the experimental set-up, given for the summer measurement of the direct greening system. Italic lines (t=8 hours) are used for the steady state calculation of the thermal resistance.

direct greening principle with *Hedera Helix*											
time (hours)	measuring points summer temperature (°C)										
	$T_{ext.}$	T_{green} surface	T_{middle} foliage	$T_{substrate}$	T_{air} cavity	$T_{ext.}$ surface (outside)	T_{cavity}	$T_{surface}$ insulation	$T_{int.\ surface}$ (inside)	$T_{int.\ surface}$ (outside)	$T_{int.}$
$t_{bare\ wall;\ 0}$	*25.28*	*--*	*--*	*--*	*--*	*24.17*	*24.06*	*23.76*	*23.30*	*23.56*	*24.02*
$t_{direct;\ 0}$	23.90	22.72	22.60	--	--	23.29	23.31	23.28	23.30	23.56	23.63
$t_{bare\ wall;\ 1}$	*34.25*	*--*	*--*	*--*	*--*	*26.22*	*24.73*	*24.47*	*23.75*	*24.01*	*24.02*
$t_{direct;\ 1}$	34.25	31.23	30.73	--	--	25.23	23.99	23.81	23.49	23.61	23.72
$t_{bare\ wall;\ 2}$	*34.98*	*--*	*--*	*--*	*--*	*27.62*	*26.06*	*25.58*	*23.84*	*24.01*	*24.02*
$t_{direct;\ 2}$	35.05	31.67	31.26	--	--	26.58	25.25	24.82	23.49	23.63	23.72
$t_{bare\ wall;\ 4}$	*34.50*	*--*	*--*	*--*	*--*	*30.02*	*28.31*	*27.49*	*24.11*	*24.01*	*24.02*
$t_{direct;\ 4}$	33.51	31.57	31.06	--	--	28.69	27.34	26.62	24.02	23.84	23.72
$t_{bare\ wall;\ 8}$	*34.84*	*--*	*--*	*--*	*--*	*32.63*	*31.29*	*30.10*	*24.54*	*24.25*	*24.13*
$t_{direct;\ 8}$	34.08	32.31	31.96	--	--	30.95	29.55	28.58	24.50	23.92	24.03

Table 5.15 Summarized data obtained by the thermocouples positioned through the experimental set-up, given for the winter measurement of the direct greening system. Italic lines (t=72 hours) are used for the steady state calculation of the thermal resistance.

direct greening principle with *Hedera Helix*											
Time (hours)	measuring points winter temperature (°C)										
	$T_{ext.}$	T_{green} surface	T_{middle} foliage	$T_{substrate}$	T_{air} cavity	$T_{ext.}$ surface (outside)	T_{cavity}	$T_{surface}$ insulation	$T_{int.\ wall}$ surface (inside)	$T_{int.\ surface}$ (outside)	$T_{int.}$
$t_{bare\ wall;\ 0}$	*24.16*	*--*	*--*	*--*	*--*	*24.43*	*24.40*	*24.32*	*23.44*	*23.98*	*23.49*
$t_{direct;\ 0}$	22.80	22.17	21.95	--	--	23.66	23.68	23.76	24.16	24.00	23.49
$t_{bare\ wall;\ 12}$	*2.61*	*--*	*--*	*--*	*--*	*5.20*	*10.93*	*12.98*	*23.24*	*23.37*	*22.95*
$t_{direct;\ 12}$	3.89	6.58	3.32	--	--	6.93	12.50	14.31	21.54	21.85	21.58
$t_{bare\ wall;\ 24}$	*0.20*	*--*	*--*	*--*	*--*	*0.12*	*4.73*	*7.50*	*21.54*	*21.85*	*21.58*
$t_{direct;\ 24}$	0.98	0.27	-0.03	--	--	3.31	8.39	10.61	21.54	21.85	21.99
$t_{bare\ wall;\ 48}$	*-4.74*	*--*	*--*	*--*	*--*	*-5.27*	*-0.82*	*2.35*	*19.61*	*19.07*	*19.07*
$t_{direct;\ 48}$	-3.68	-3.62	-3.91	--	--	-2.69	1.68	4.66	19.99	20.46	20.57
$t_{bare\ wall;\ 72}$	*-7.62*	*--*	*--*	*--*	*--*	*-6.64*	*-2.35*	*0.81*	*17.05*	*17.65*	*17.85*
$t_{direct;\ 72}$	-6.19	-6.16	-6.42	--	--	-4.91	-0.48	2.61	18.57	19.18	19.87

5.5.2 Measuring *Hedera helix* (indirect façade greening principle)

Figure 5.38 Roughly 1 m² of Hedera helix placed in a container filled with soil to ensure the plants vitality during the measurements inside the box. The climber attached to a trellis was mounted 10 cm from the façade to guarantee an air cavity and simulate indirect façade greenery.

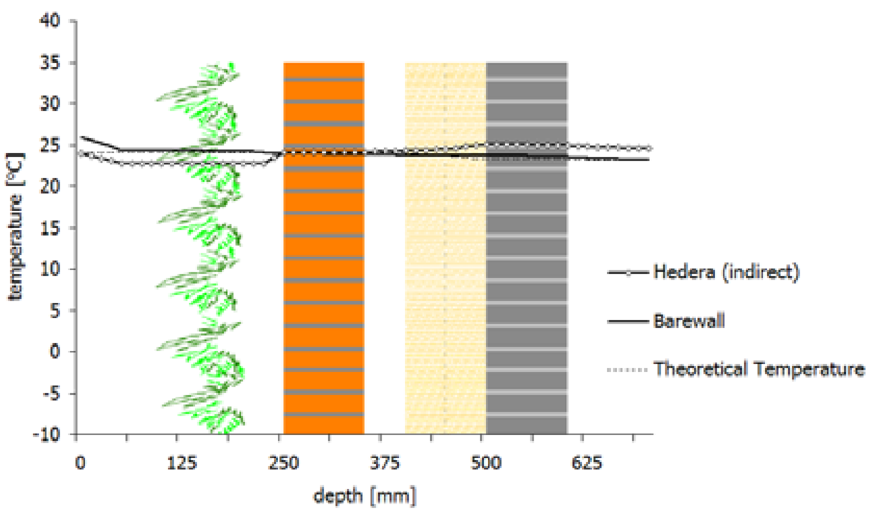

Figure 39 Temperature development at the beginning of the summer measurement, for a bare wall compared with an indirect greening principle; t=0 hour.

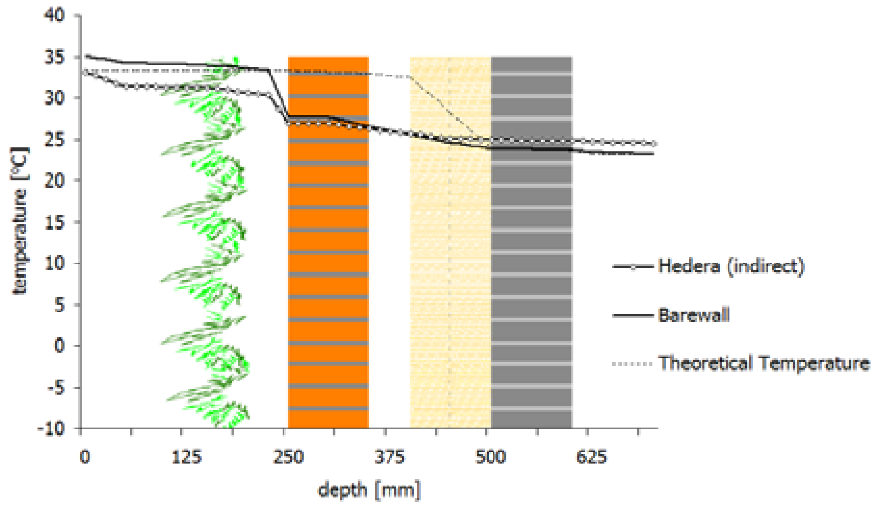

Figure 40 Temperature development after 2 hours of heating (35 °C), for a bare wall compared with an indirect greening principle; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

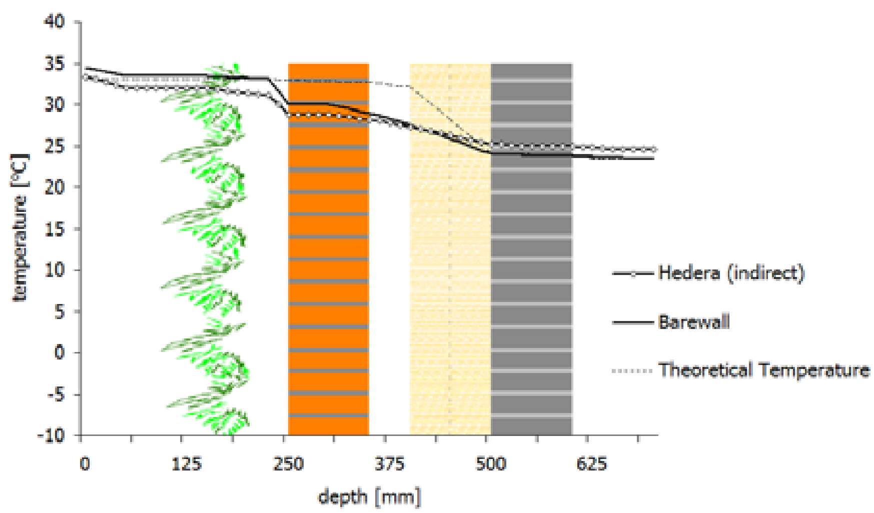

Figure 41 Temperature development after 4 hours of heating (35 °C), for a bare wall compared with an indirect greening principle; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

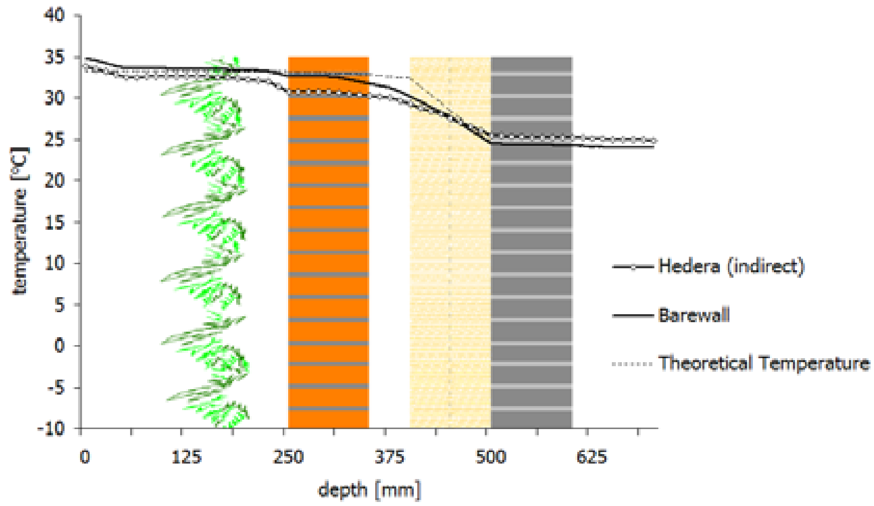

Figure 42 Temperature development after 8 hours of heating (35 °C), for a bare wall compared with an indirect greening principle; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

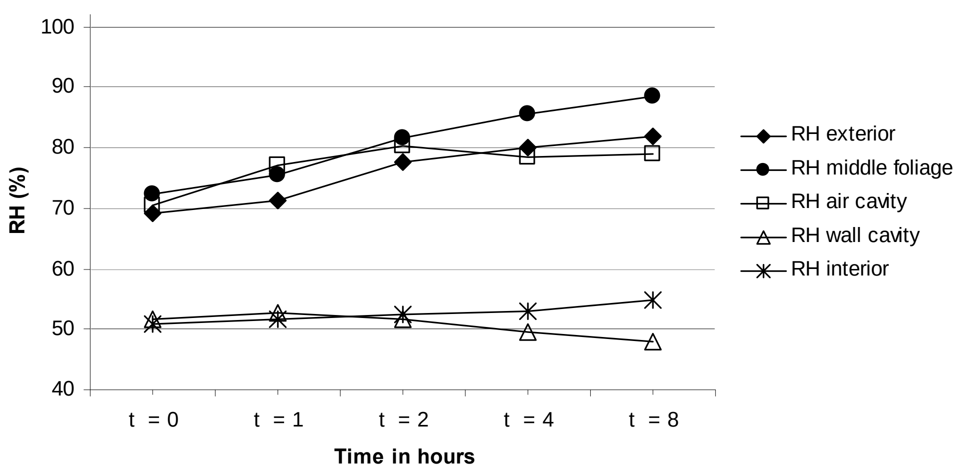

Figure 43 Humidity development over different time steps, for a bare wall compared with an indirect greening principle, given for the summer measurement.

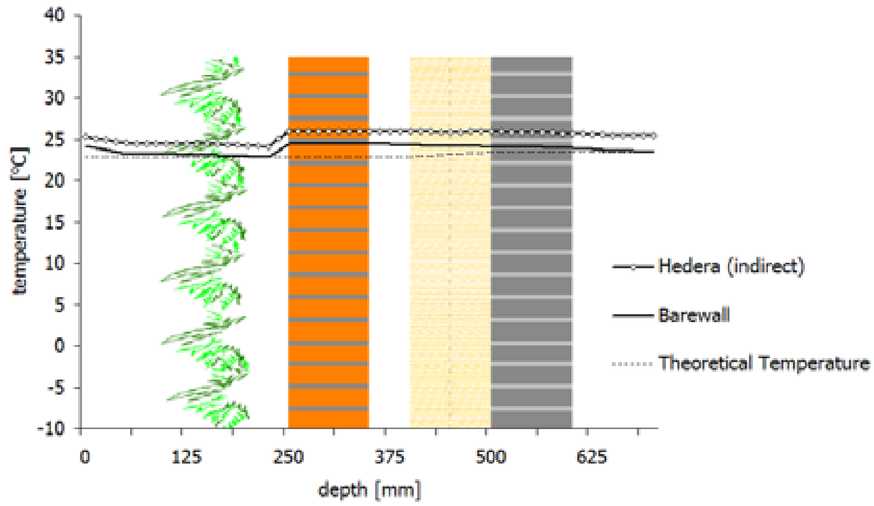

Figure 44 Temperature development at the beginning of the winter measurement, for a bare wall compared with an indirect greening principle; t=0 hour.

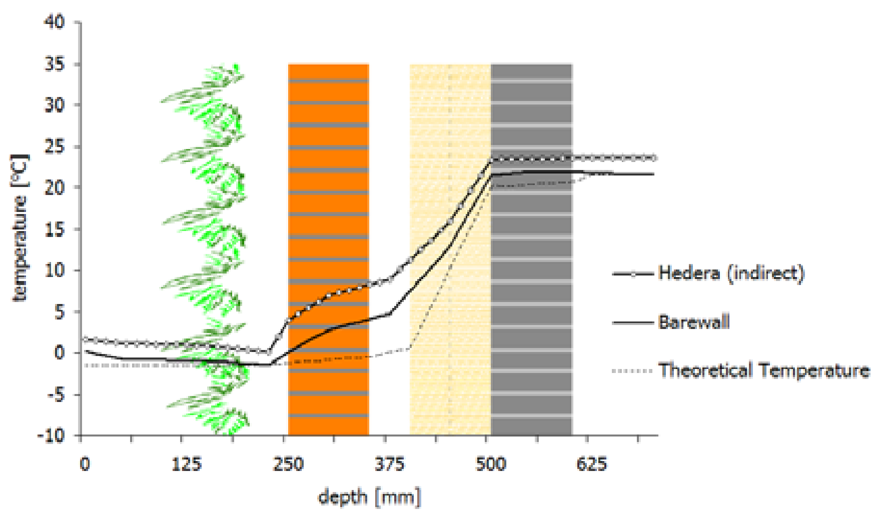

Figure 45 Temperature development after 24 hours of cooling, for a bare wall compared with an indirect greening principle; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

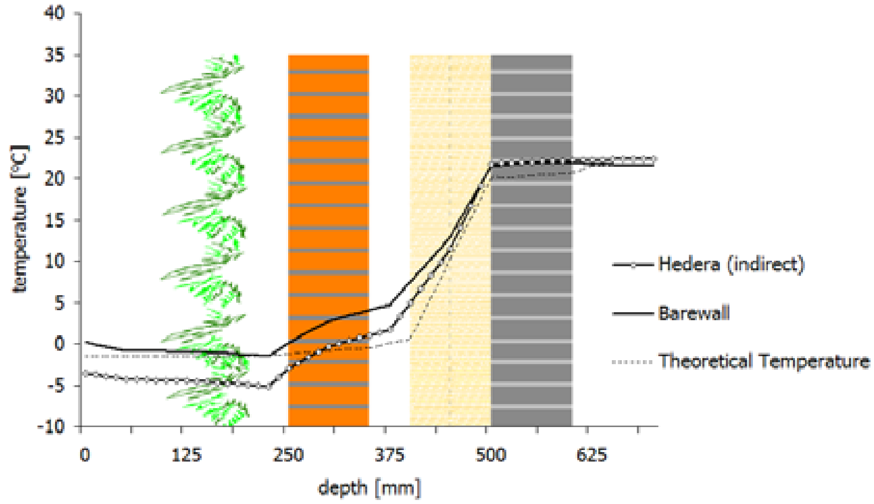

Figure 46 Temperature development after 48 hours of cooling, for a bare wall compared with an indirect greening principle; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

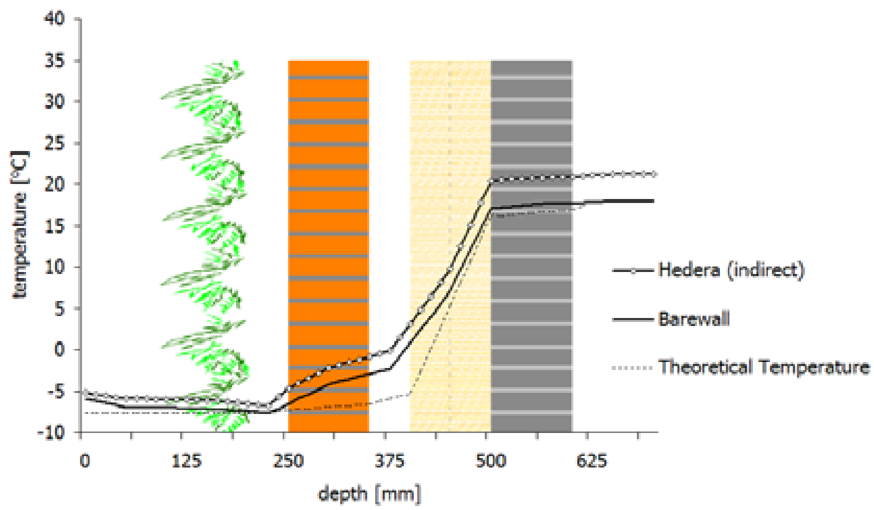

Figure 47 Temperature development after 72 hours of cooling, for a bare wall compared with an indirect greening principle; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

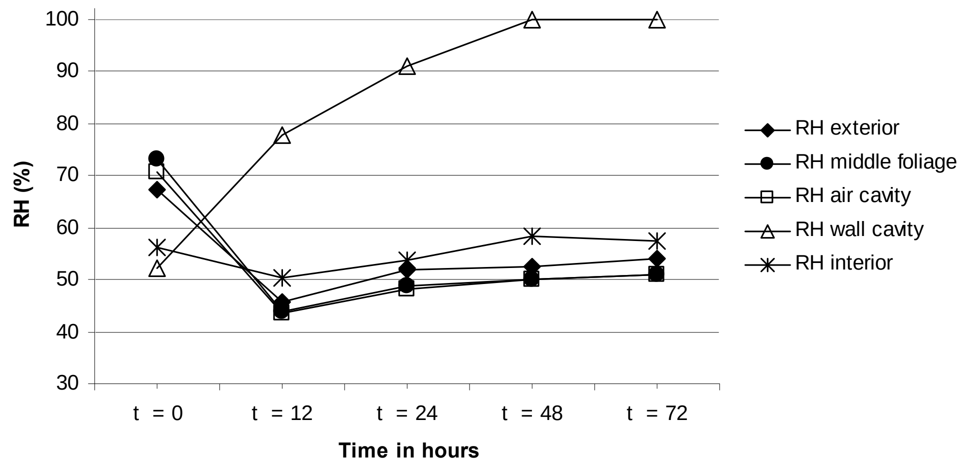

Figure 48 Humidity development over different time steps, for a bare wall compared with an indirect greening principle, given for the winter measurement.

Table 5.16 Summarized data obtained by the thermocouples positioned through the experimental set-up, given for the summer measurement of the indirect greening system. Italic lines (t=8 hours) are used for the steady state calculation of the thermal resistance.

indirect greening principle with *Hedera Helix*											
Time (hours)	measuring points summer temperature (°C)										
	$T_{ext.}$	$T_{green\ surface}$	$T_{middle\ foliage}$	$T_{substrate}$	$T_{air\ cavity}$	$T_{ext.\ wall\ surface}$	T_{cavity}	$T_{surface\ insulation}$	$T_{int.\ surface\ (inside)}$	$T_{int.\ surface\ (outside)}$	$T_{int.}$
$t_{bare\ wall;\ 0}$	*25.28*	--	--	--	--	*24.17*	*24.06*	*23.76*	*23.30*	*23.56*	*24.02*
$t_{indirect;\ 0}$	24.10	24.07	24.12	--	24.86	24.11	24.06	24.03	25.06	24.96	24.93
$t_{bare\ wall;\ 1}$	*34.25*	--	--	--	--	*26.22*	*24.73*	*24.47*	*23.75*	*24.01*	*24.02*
$t_{indirect;\ 1}$	33.10	31.46	31.36	--	30.51	25.85	24.73	24.81	25.01	24.77	24.70
$t_{bare\ wall;\ 2}$	*34.98*	--	--	--	--	*27.62*	*26.06*	*25.58*	*23.84*	*24.01*	*24.02*
$t_{indirect;\ 2}$	33.13	31.29	31.25	--	30.34	26.95	26.06	25.58	24.95	24.86	24.72
$t_{bare\ wall;\ 4}$	*34.50*	--	--	--	--	*30.02*	*28.31*	*27.49*	*24.11*	*24.01*	*24.02*
$t_{indirect;\ 4}$	33.07	31.92	31.92	--	31.16	28.83	27.83	27.30	25.21	24.89	24.75
$t_{bare\ wall;\ 8}$	*34.84*	--	--	--	--	*32.63*	*31.29*	*30.10*	*24.54*	*24.25*	*24.13*
$t_{indirect;\ 8}$	33.82	32.57	32.63	--	31.99	30.78	30.02	29.20	25.49	25.19	24.86

Table 5.17 Summarized data obtained by the thermocouples positioned through the experimental set-up, given for the winter measurement of the indirect greening system. Italic lines (t=72 hours) are used for the steady state calculation of the thermal resistance.

indirect greening principle with *Hedera Helix*											
Time (hours)	measuring points winter temperature (°C)										
	$T_{ext.}$	$T_{green\ surface}$	$T_{middle\ foliage}$	$T_{substrate}$	$T_{air\ cavity}$	$T_{ext.\ surface\ (outside)}$	T_{cavity}	$T_{surface\ insulation}$	$T_{int.\ wall\ surface\ (inside)}$	$T_{int.\ surface\ (outside)}$	$T_{int.}$
$t_{bare\ wall;\ 0}$	*24.16*	--	--	--	--	*24.43*	*24.40*	*24.32*	*23.44*	*23.98*	*23.49*
$t_{indirect;\ 0}$	24.59	23.67	23.51	--	22.60	25.93	25.94	25.90	25.88	25.71	24.89
$t_{bare\ wall;\ 12}$	*2.61*	--	--	--	--	*5.20*	*10.93*	*12.98*	*23.24*	*23.37*	*22.95*
$t_{indirect;\ 12}$	5.54	5.12	5.00	--	4.25	8.31	13.58	15.47	25.16	25.16	24.91
$t_{bare\ wall;\ 24}$	*0.20*	--	--	--	--	*0.12*	*4.73*	*7.50*	*21.54*	*21.85*	*21.58*
$t_{indirect;\ 24}$	1.13	1.00	0.86	--	0.09	3.94	8.89	11.25	23.38	23.55	23.53
$t_{bare\ wall;\ 48}$	*-4.74*	--	--	--	--	*-5.27*	*-0.82*	*2.35*	*19.61*	*19.07*	*19.07*
$t_{indirect;\ 48}$	-4.29	-4.43	-4.56	--	-5.17	-2.93	1.73	4.99	21.75	22.18	22.33
$t_{bare\ wall;\ 72}$	*-7.62*	--	--	--	--	*-6.64*	*-2.35*	*0.81*	*17.05*	*17.65*	*17.85*
$t_{indirect;\ 72}$	-5.94	-6.03	-6.12	--	-6.73	-4.72	-0.18	3.14	19.99	20.70	21.28

5.5.3 Measuring Living Wall System; based on planter boxes

Figure 5.49 Planter box system as used inside the experimental set-up. The air cavity of 5 cm between living wall system and façade is clearly visible. Plant species used in this living wall system: Lamium galeobdolon, Carex, Alchemilla and Hosta.

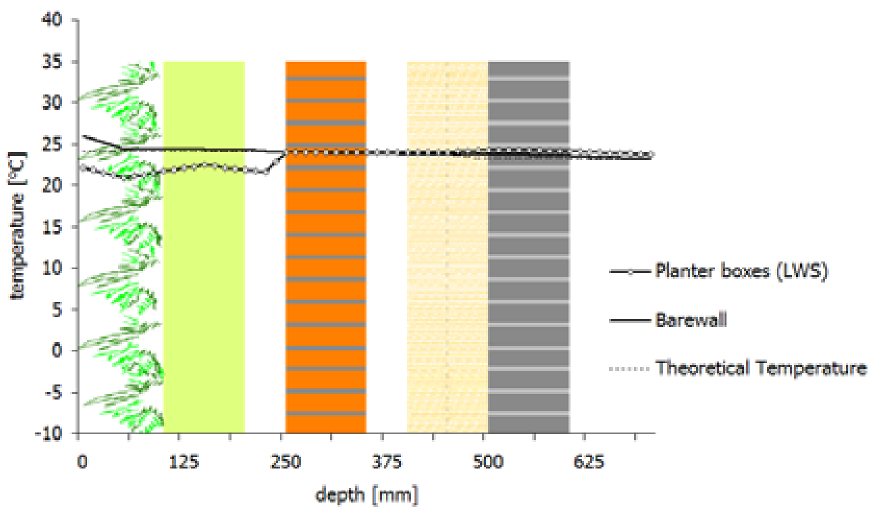

Figure 50 Temperature development at the beginning of the summer measurement, for a bare wall compared with a living wall system based on planter boxes; t=0 hour.

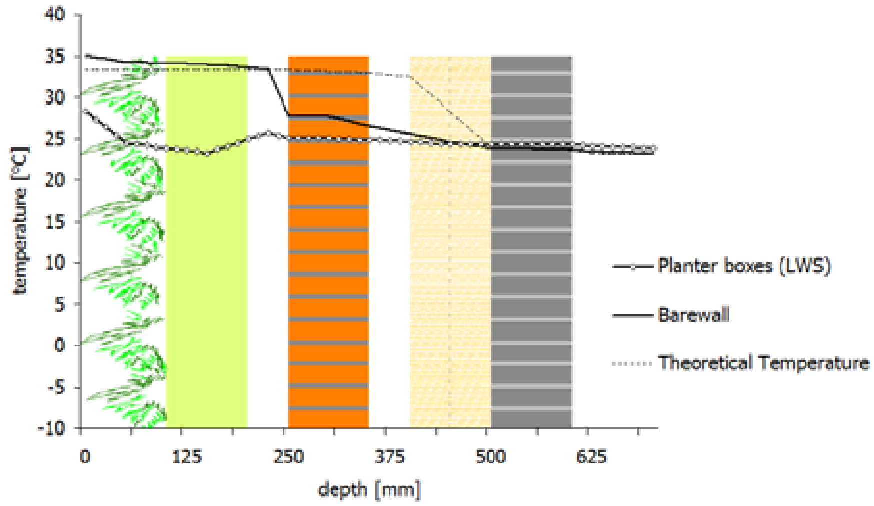

Figure 51 Temperature development after 2 hours of heating (35 °C), for a bare wall compared with a living wall system based on planter boxes; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

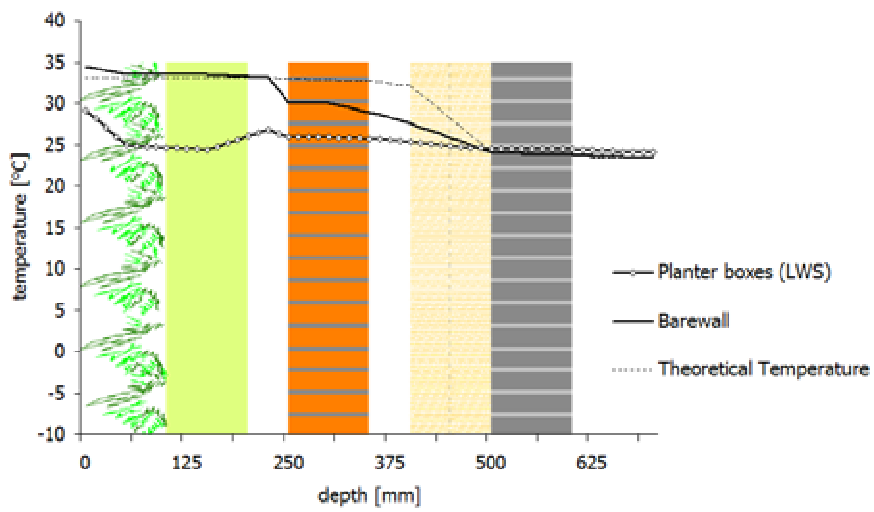

Figure 52 Temperature development after 4 hours of heating (35 °C), for a bare wall compared with a living wall system based on planter boxes; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

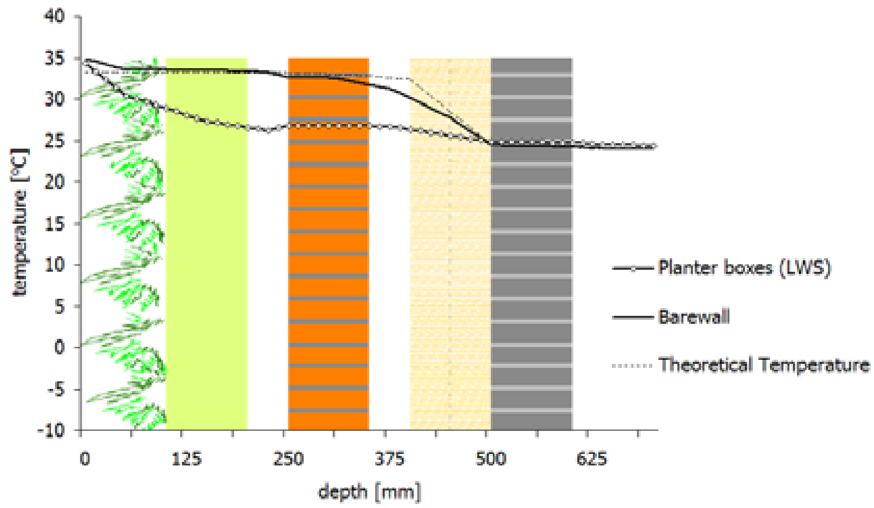

Figure 53 Temperature development after 8 hours of heating (35 °C), for a bare wall compared with a living wall system based on planter boxes; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

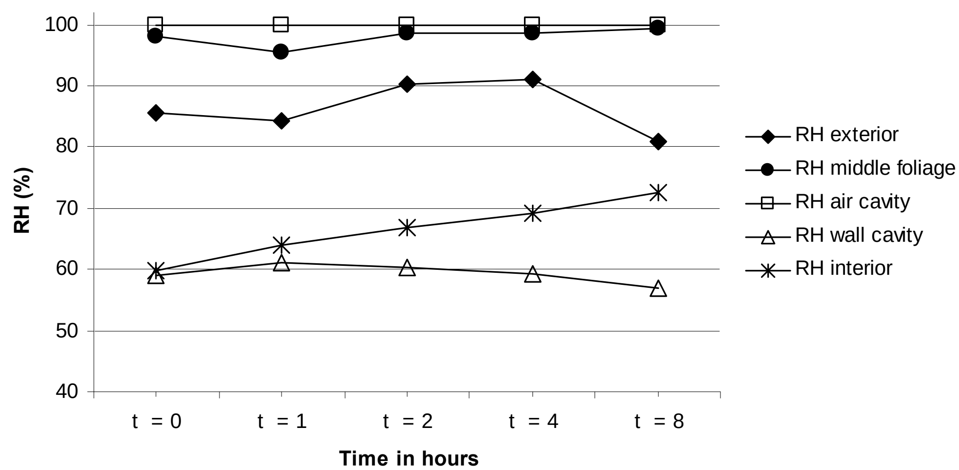

Figure 54 Humidity development over different time steps, for a bare wall compared with a living wall system based on planter boxes, given for the summer measurement.

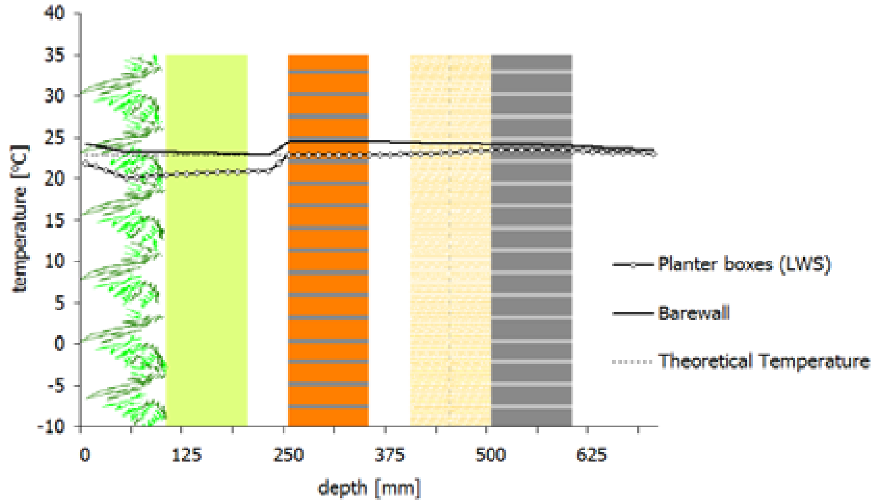

Figure 55 Temperature development at the beginning of the winter measurement, for a bare wall compared with a living wall system based on planter boxes; t=0 hour.

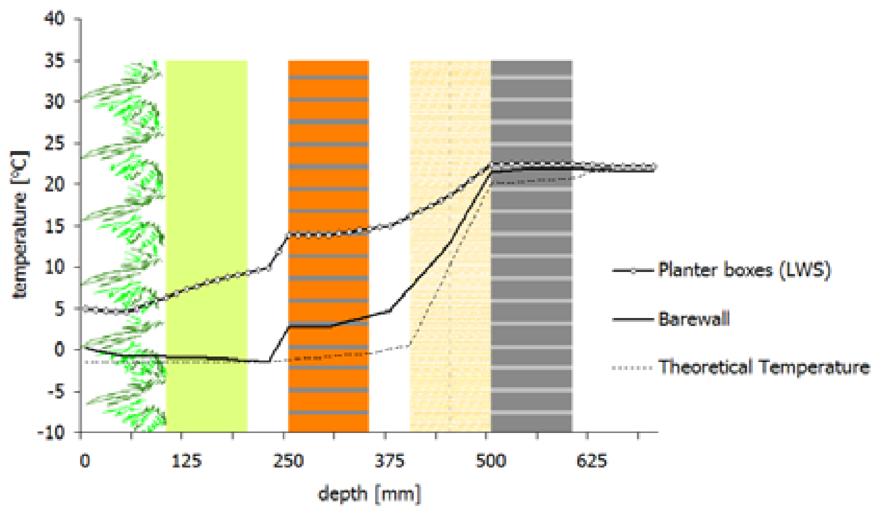

Figure 56 Temperature development after 24 hours of cooling, for a bare wall compared with a living wall system based on planter boxes; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

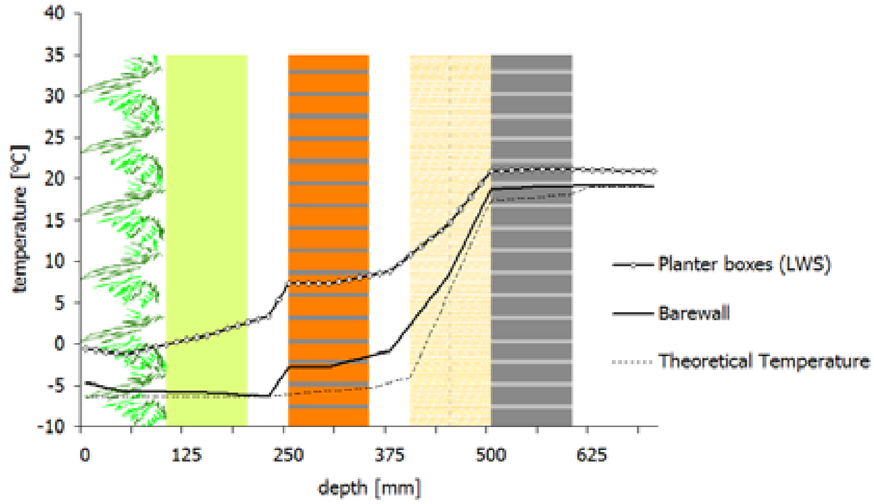

Figure 57 Temperature development after 48 hours of cooling, for a bare wall compared with a living wall system based on planter boxes; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

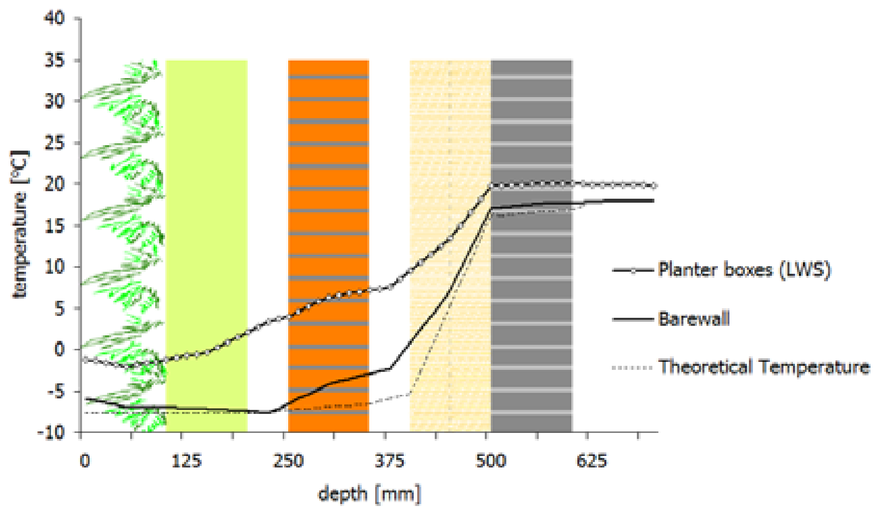

Figure 58 Temperature development after 72 hours of cooling, for a bare wall compared with a living wall system based on planter boxes; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

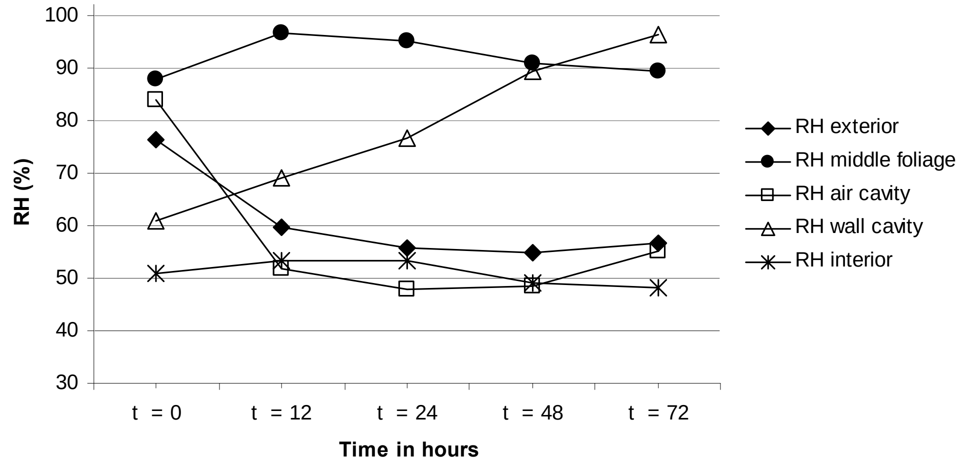

Figure 59 Humidity development over different time steps, for a bare wall compared with a living wall system based on planter boxes, given for the winter measurement.

Table 5.18 Summarized data obtained by the thermocouples positioned through the experimental set-up, given for the summer measurement of the living wall system based on planter boxes. Italic lines (t=8 hours) are used for the steady state calculation of the thermal resistance.

Living wall system based on planter boxes											
Time (hours)	measuring points summer temperature (°C)										
	$T_{ext.}$	$T_{green\ surface}$	$T_{middle\ foliage}$	$T_{substrate}$	$T_{air\ cavity}$	$T_{ext.\ wall\ surface}$	T_{cavity}	$T_{surface\ insulation}$	$T_{int.\ surface\ (inside)}$	$T_{int.\ surface\ (outside)}$	$T_{int.}$
$t_{bare\ wall;\ 0}$	*25.28*	--	--	--	--	*24.17*	*24.06*	*23.76*	*23.30*	*23.56*	*24.02*
$t_{planter;\ 0}$	23.36	23.36	20.94	21.69	21.59	24.11	24.06	24.03	24.17	24.13	23.64
$t_{bare\ wall;\ 1}$	*34.25*	--	--	--	--	*26.22*	*24.73*	*24.47*	*23.75*	*24.01*	*24.02*
$t_{planter;\ 1}$	27.65	27.65	23.77	23.26	24.95	24.54	24.34	24.27	24.31	24.18	23.76
$t_{bare\ wall;\ 2}$	*34.98*	--	--	--	--	*27.62*	*26.06*	*25.58*	*23.84*	*24.01*	*24.02*
$t_{planter;\ 2}$	28.27	28.27	24.45	23.86	25.72	25.01	24.71	24.58	24.33	24.28	24.15
$t_{bare\ wall;\ 4}$	*34.50*	--	--	--	--	*30.02*	*28.31*	*27.49*	*24.11*	*24.01*	*24.02*
$t_{planter;\ 4}$	29.20	29.20	24.89	24.61	26.83	25.88	25.62	25.34	24.13	24.41	24.08
$t_{bare\ wall;\ 8}$	*34.84*	--	--	--	--	*32.63*	*31.29*	*30.10*	*24.54*	*24.25*	*24.13*
$t_{planter;\ 8}$	34.83	34.83	30.39	28.84	26.18	26.85	26.67	26.30	24.54	24.72	24.35

Table 5.19 Summarized data obtained by the thermocouples positioned through the experimental set-up, given for the winter measurement of the living wall system based on planter boxes. Italic lines (t=8 hours) are used for the steady state calculation of the thermal resistance.

Living wall system based on planter boxes											
Time (hours)	measuring points winter temperature (°C)										
	$T_{ext.}$	$T_{green\ surface}$	$T_{middle\ foliage}$	$T_{substrate}$	$T_{air\ cavity}$	$T_{ext.\ wall\ surface}$	T_{cavity}	$T_{surface\ insulation}$	$T_{int.\ surface\ (inside)}$	$T_{int.\ surface\ (outside)}$	$T_{int.}$
$t_{bare\ wall;\ 0}$	*24.16*	--	--	--	--	*24.43*	*24.40*	*24.32*	*23.44*	*23.98*	*23.49*
$t_{planter;\ 0}$	21.91	21.91	20.03	20.35	20.91	22.81	22.85	22.87	23.44	23.46	23.01
$t_{bare\ wall;\ 12}$	*2.61*	--	--	--	--	*5.20*	*10.93*	*12.98*	*23.24*	*23.37*	*22.95*
$t_{planter;\ 12}$	10.66	10.66	10.03	10.89	14.31	15.18	19.11	19.81	23.24	23.37	22.95
$t_{bare\ wall;\ 24}$	*0.20*	--	--	--	--	*0.12*	*4.73*	*7.50*	*21.54*	*21.85*	*21.58*
$t_{planter;\ 24}$	4.92	4.92	4.52	5.88	9.60	11.50	14.98	16.19	22.36	22.44	22.00
$t_{bare\ wall;\ 48}$	*-4.74*	--	--	--	--	*-5.27*	*-0.82*	*2.35*	*19.61*	*19.07*	*19.07*
$t_{planter;\ 48}$	-0.62	-0.62	-1.24	-0.38	3.31	4.89	8.56	10.79	20.86	21.09	20.88
$t_{bare\ wall;\ 72}$	*-7.62*	--	--	--	--	*-6.64*	*-2.35*	*0.81*	*17.05*	*17.65*	*17.85*
$t_{planter;\ 72}$	-2.09	-2.09	-2.97	-1.22	3.39	3.99	7.53	9.49	19.70	19.99	20.01

5.5.4 Measuring Living Wall System; based on mineral (stone) wool

Figure 5.60 Living wall based on mineral wool panels as placed inside the climate chamber. The air cavity between panels and façade was 5 cm. Plant species used: Ferns, Geraniums and Carex.

Figure 5.61 Cross section of the living wall panel filled with mineral wool as substrate.

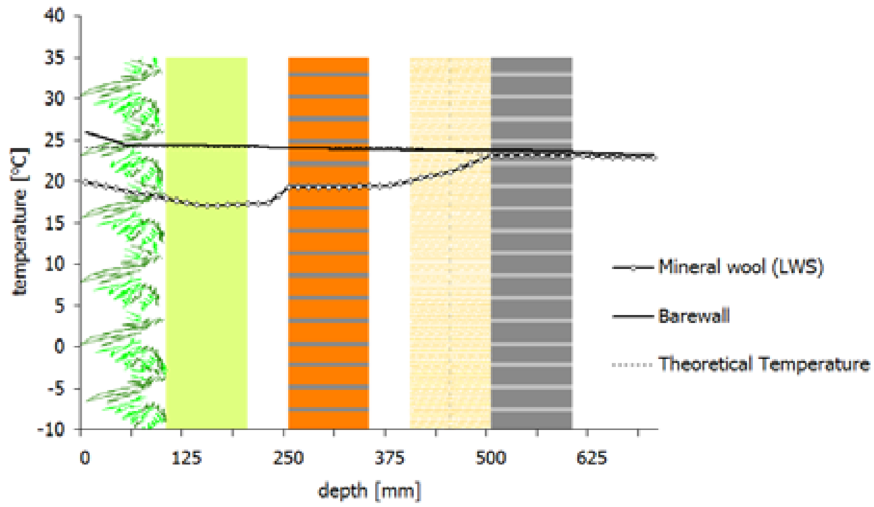

Figure 5.62 Temperature development at the beginning of the summer measurement, for a bare wall compared with a living wall system based on mineral wool; t=0 hour.

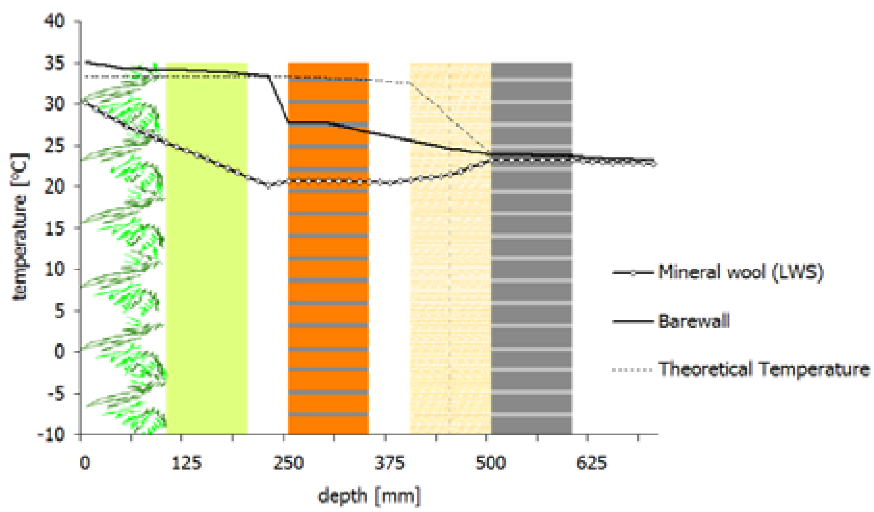

Figure 5.63 Temperature development after 2 hours of heating (35 °C), for a bare wall compared with a living wall system based on mineral wool; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

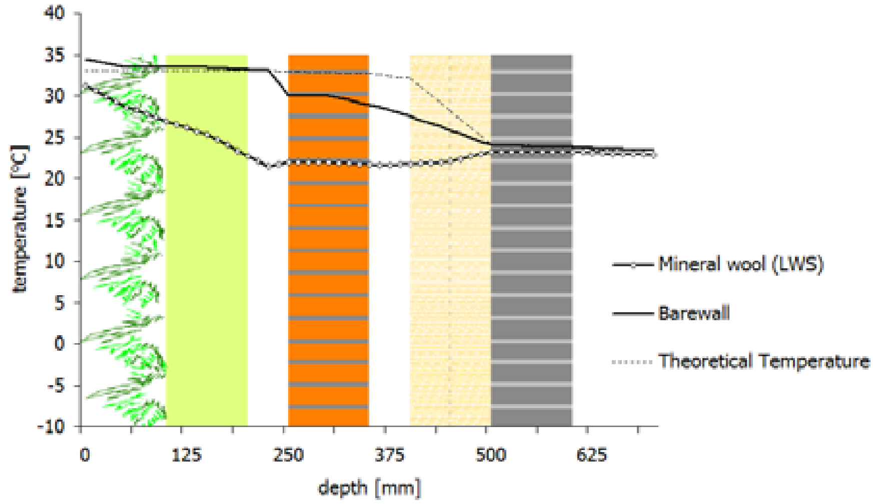

Figure 5.64 Temperature development after 4 hours of heating (35 °C), for a bare wall compared with a living wall system based on mineral wool; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

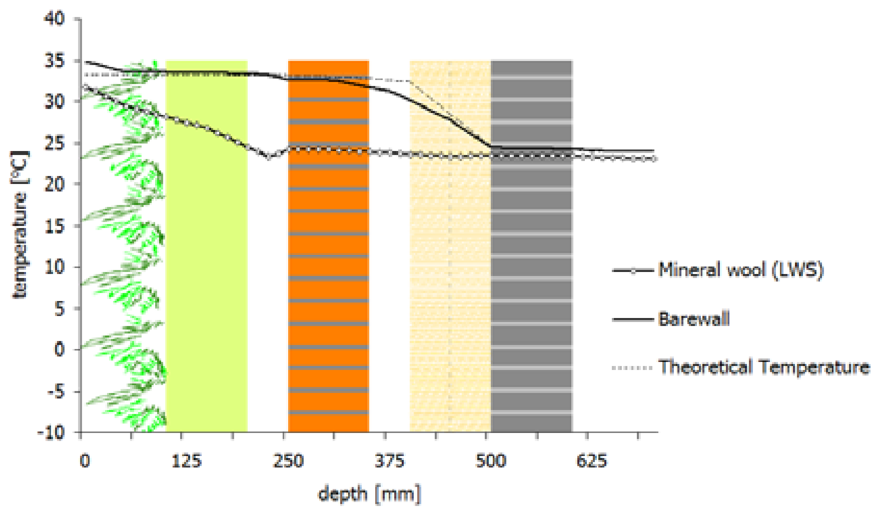

Figure 5.65 Temperature development after 8 hours of heating (35 °C), for a bare wall compared with a living wall system based on mineral wool; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

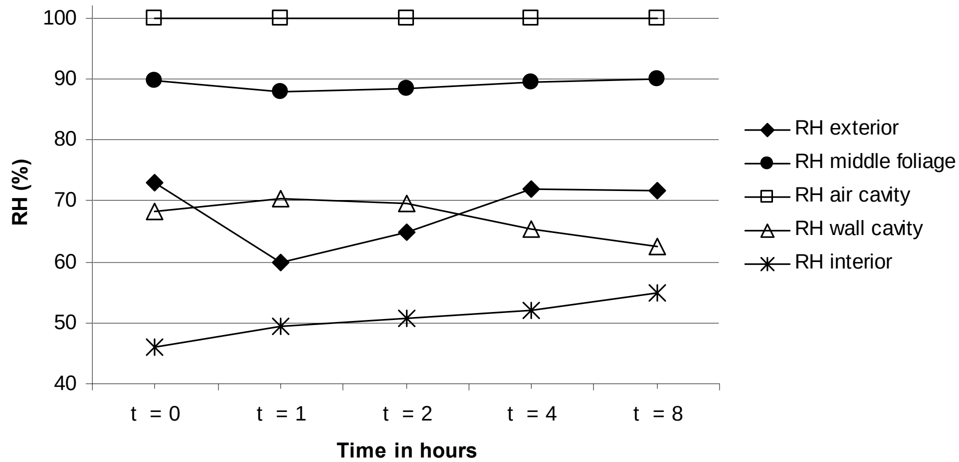

Figure 5.66 Humidity development over different time steps, for a bare wall compared with a living wall system based on mineral wool, given for the summer measurement.

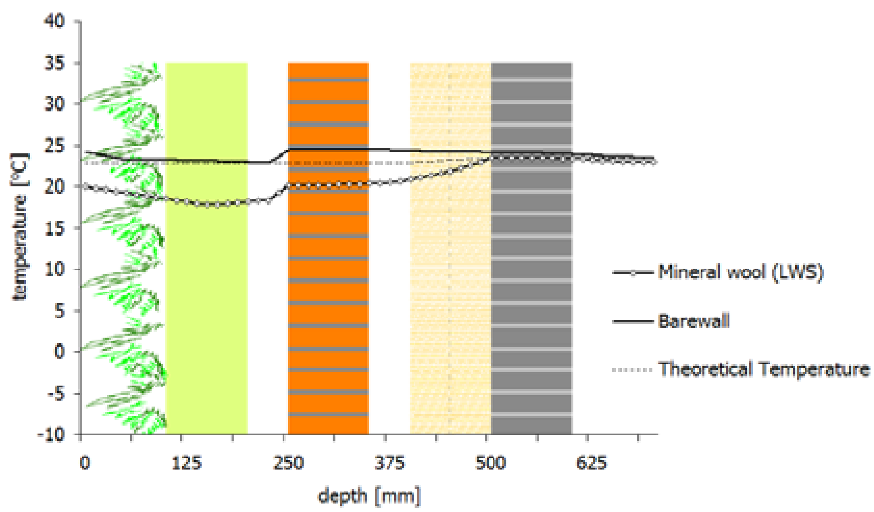

Figure 5.67 Temperature development at the beginning of the winter measurement, for a bare wall compared with a living wall system based on mineral wool; t=0 hour.

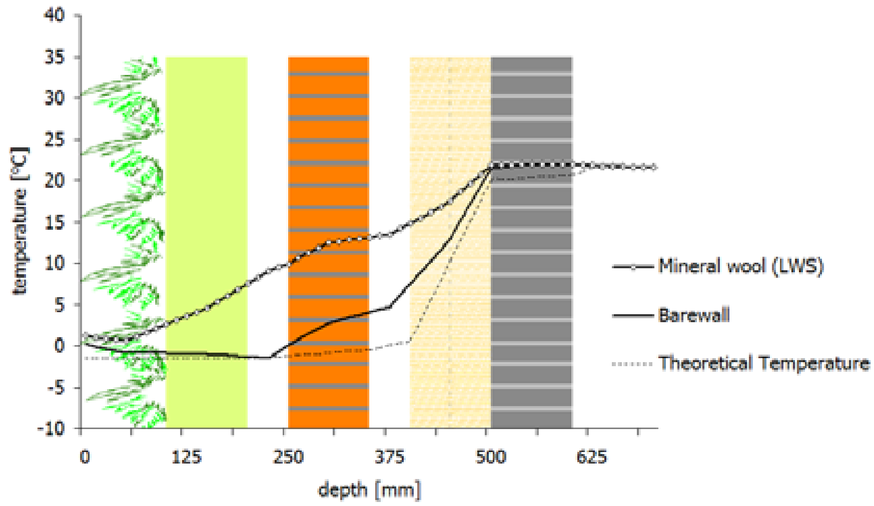

Figure 5.68 Temperature development after 24 hours of cooling, for a bare wall compared with a living wall system based on mineral wool; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

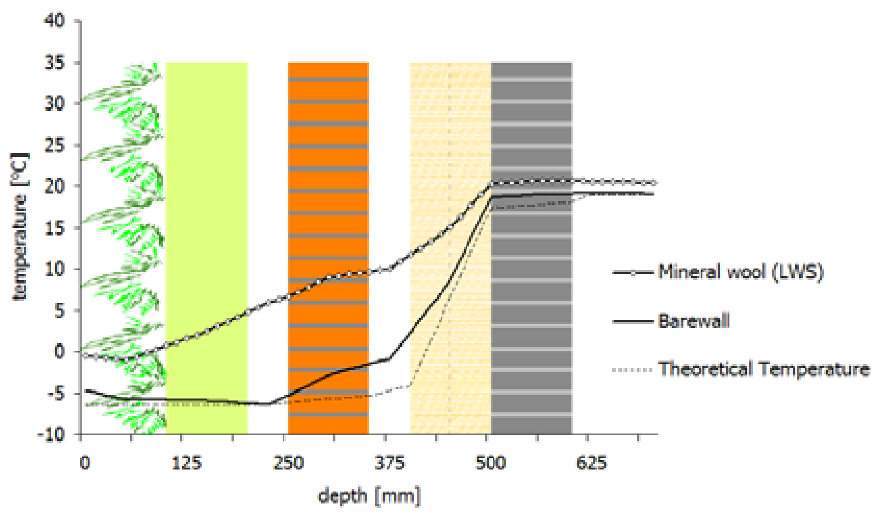

Figure 5.69 Temperature development after 48 hours of cooling, for a bare wall compared with a living wall system based on mineral wool; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

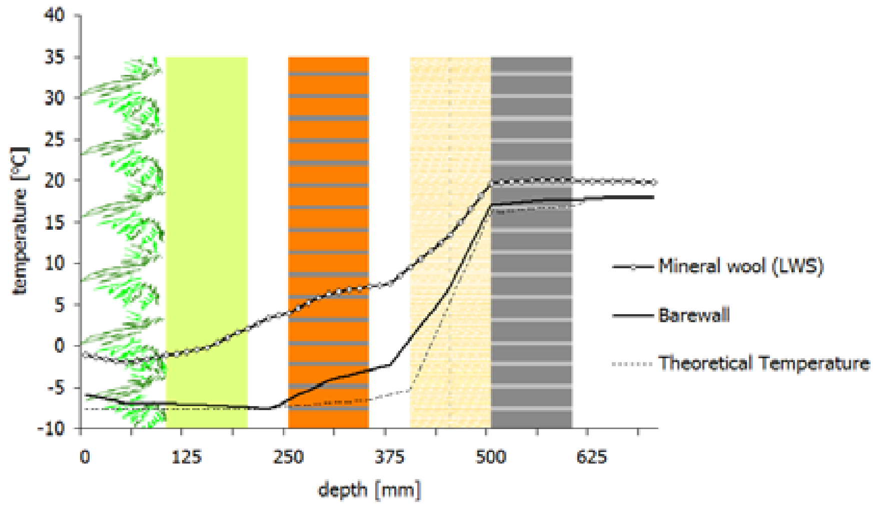

Figure 5.70 Temperature development after 72 hours of cooling, for a bare wall compared with a living wall system based on mineral wool; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

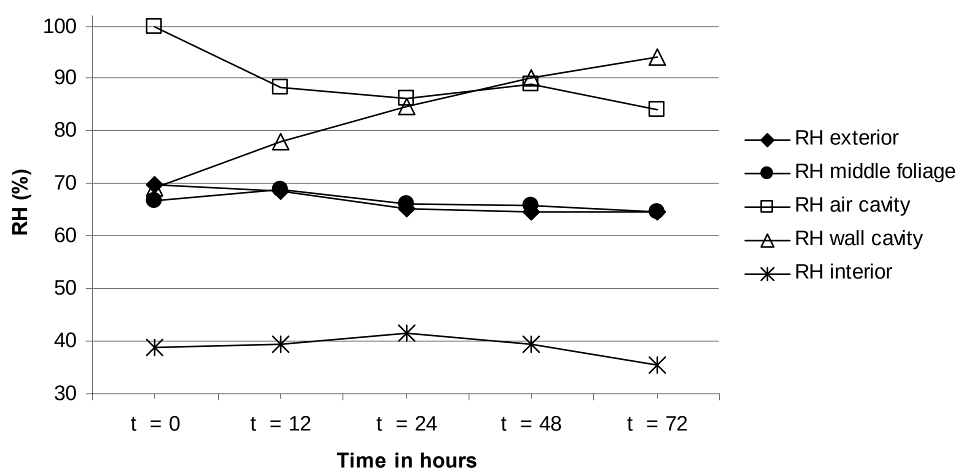

Figure 5.71 Humidity development over different time steps, for a bare wall compared with a living wall system based on mineral wool, given for the winter measurement.

Table 5.20 Summarized data obtained by the thermocouples positioned through the experimental set-up, given for the summer measurement of the living wall system based on mineral wool. Italic lines (t=8 hours) are used for the steady state calculation of the thermal resistance.

Living wall system based on mineral wool											
Time (hours)	measuring points summer temperature (°C)										
	$T_{ext.}$	$T_{green\ surface}$	$T_{middle\ foliage}$	$T_{substrate}$	$T_{air\ cavity}$	$T_{ext.\ wall\ surface}$	T_{cavity}	$T_{surface\ insulation}$	$T_{int.\ surface\ (inside)}$	$T_{int.\ surface\ (outside)}$	$T_{int.}$
$t_{bare\ wall;\ 0}$	*25.28*	--	--	--	--	*24.17*	*24.06*	*23.76*	*23.30*	*23.56*	*24.02*
$t_{mineral;\ 0}$	23.34	23.34	20.71	19.11	17.75	19.20	19.61	20.12	23.30	23.56	23.27
$t_{bare\ wall;\ 1}$	*34.25*	--	--	--	--	*26.22*	*24.73*	*24.47*	*23.75*	*24.01*	*24.02*
$t_{mineral;\ 1}$	29.09	29.09	26.22	23.51	19.34	19.97	19.85	20.29	23.16	23.50	23.42
$t_{bare\ wall;\ 2}$	*34.98*	--	--	--	--	*27.62*	*26.06*	*25.58*	*23.84*	*24.01*	*24.02*
$t_{mineral;\ 2}$	30.09	30.09	27.26	25.29	20.09	20.65	20.41	20.76	23.19	23.98	23.75
$t_{bare\ wall;\ 4}$	*34.50*	--	--	--	--	*30.02*	*28.31*	*27.49*	*24.11*	*24.01*	*24.02*
$t_{mineral;\ 4}$	31.21	31.21	28.64	26.96	21.48	21.95	21.59	21.75	23.25	23.23	22.89
$t_{bare\ wall;\ 8}$	*34.84*	--	--	--	--	*32.63*	*31.29*	*30.10*	*24.54*	*24.25*	*24.13*
$t_{mineral;\ 8}$	31.76	31.76	29.42	28.11	23.32	24.20	23.79	23.64	23.49	23.42	23.11

Table 5.21 Summarized data obtained by the thermocouples positioned through the experimental set-up, given for the winter measurement of the living wall system based on mineral wool. Italic lines (t=72 hours) are used for the steady state calculation of the thermal resistance.

Living wall system based on mineral wool											
Time (hours)	measuring points winter temperature (°C)										
	$T_{ext.}$	$T_{green\ surface}$	$T_{middle\ foliage}$	$T_{substrate}$	$T_{air\ cavity}$	$T_{ext.\ wall\ surface}$	T_{cavity}	$T_{surface\ insulation}$	$T_{int.\ surface\ (inside)}$	$T_{int.\ surface\ (outside)}$	$T_{int.}$
$t_{bare\ wall;\ 0}$	*24.16*	--	--	--	--	*24.43*	*24.40*	*24.32*	*23.44*	*23.98*	*23.49*
$t_{mineral;\ 0}$	20.01	20.01	19.22	18.66	18.33	20.14	20.44	20.90	23.44	23.46	23.05
$t_{bare\ wall;\ 12}$	*2.61*	--	--	--	--	*5.20*	*10.93*	*12.98*	*23.24*	*23.37*	*22.95*
$t_{mineral;\ 12}$	3.89	3.89	2.81	5.09	11.91	13.04	16.82	17.85	23.24	23.37	22.95
$t_{bare\ wall;\ 24}$	*0.20*	--	--	--	--	*0.12*	*4.73*	*7.50*	*21.54*	*21.85*	*21.58*
$t_{mineral;\ 24}$	1.04	1.04	0.59	2.56	8.98	9.93	13.30	14.81	21.83	21.85	21.58
$t_{bare\ wall;\ 48}$	*-4.74*	--	--	--	--	*-5.27*	*-0.82*	*2.35*	*19.61*	*19.07*	*19.07*
$t_{mineral;\ 48}$	-0.44	-0.44	-1.04	0.71	5.95	6.66	10.02	11.69	20.31	20.59	20.41
$t_{bare\ wall;\ 72}$	*-7.62*	--	--	--	--	*-6.64*	*-2.35*	*0.81*	*17.05*	*17.65*	*17.85*
$t_{mineral;\ 72}$	-1.19	-1.19	-2.10	-1.24	3.38	3.98	7.57	9.52	19.70	20.02	19.96

5.5.5 Measuring Living Wall System; based on aminoplast foam

Figure 5.72 A living wall system based on foam substrate, thickness of the foam is 18 cm. Again an air cavity is visible of 5 cm between panel and façade. Plant species used for this test are Geraniums.

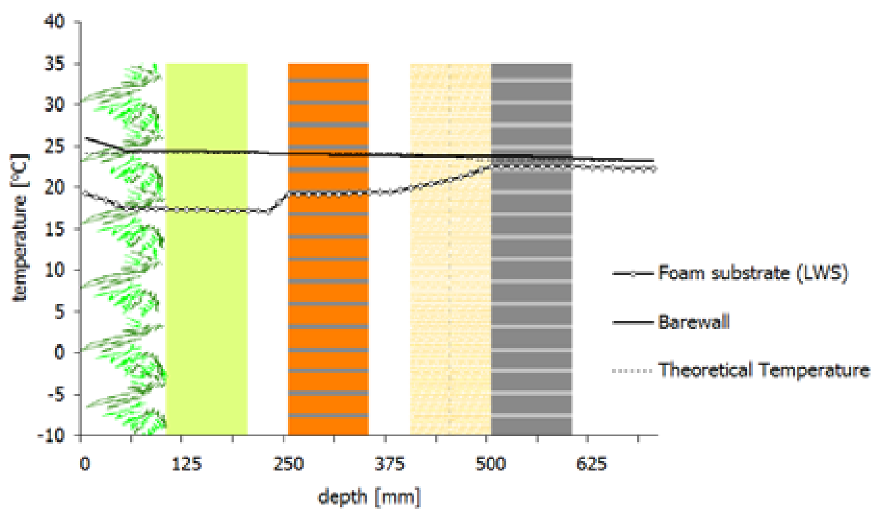

Figure 5.73 Temperature development at the beginning of the summer measurement, for a bare wall compared with a living wall system based on foam substrate; t=0 hour.

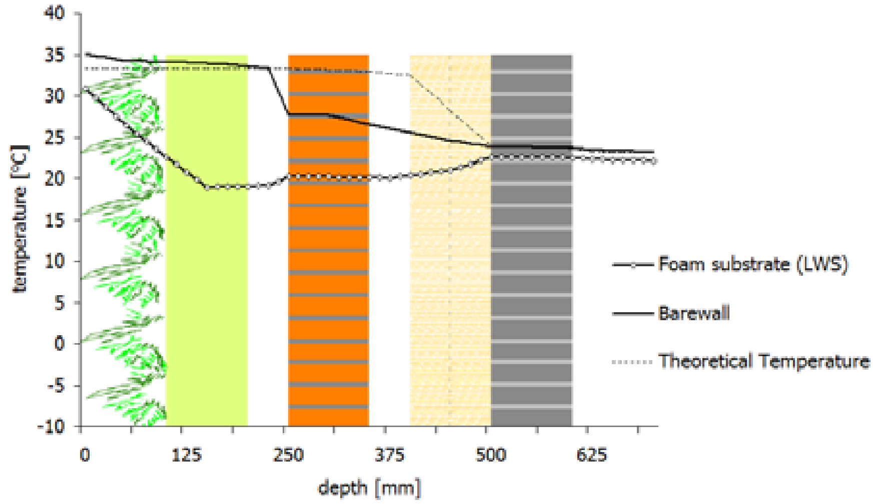

Figure 5.74 Temperature development after 2 hours of heating (35 °C), for a bare wall compared with a living wall system based on foam substrate; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

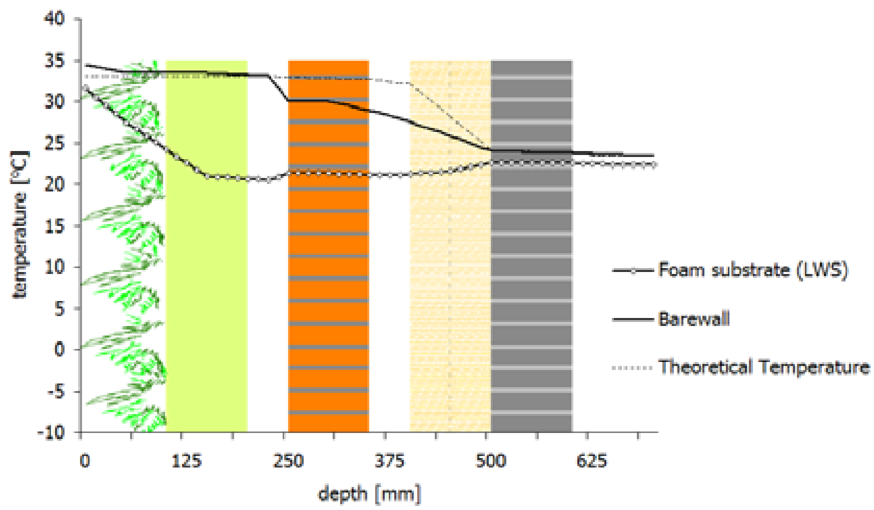

Figure 5.75 Temperature development after 4 hours of heating (35 °C), for a bare wall compared with a living wall system based on foam substrate; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

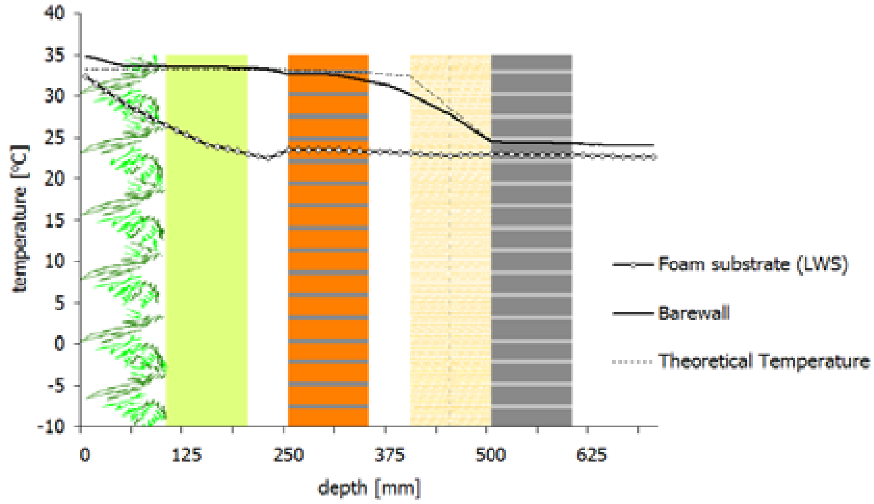

Figure 5.76 Temperature development after 8 hours of heating (35 °C), for a bare wall compared with a living wall system based on foam substrate; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

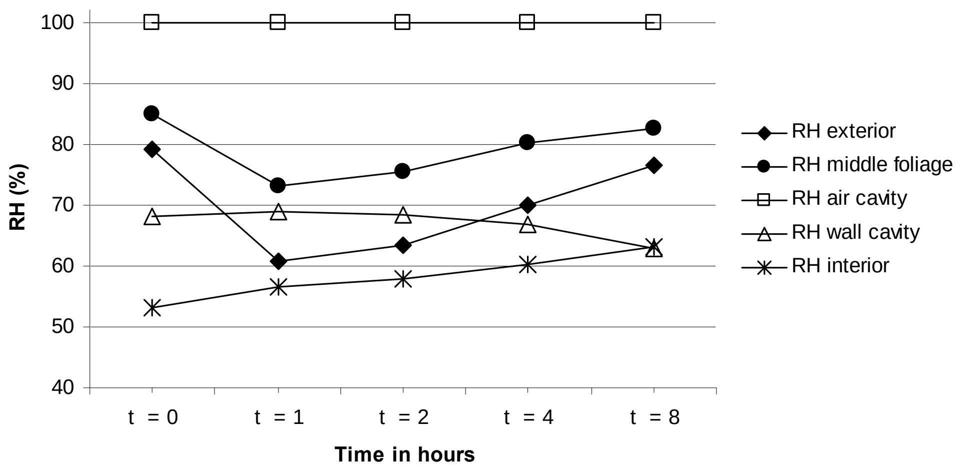

Figure 5.77 Humidity development over different time steps, for a bare wall compared with a living wall system based on foam substrate, given for the summer measurement.

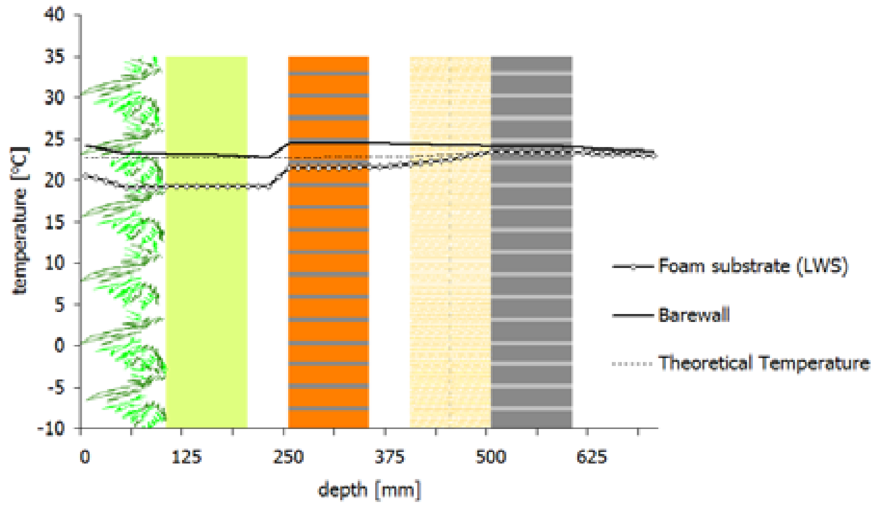

Figure 5.78 Temperature development at the beginning of the winter measurement, for a bare wall compared with a living wall system based on foam substrate; t=0 hour.

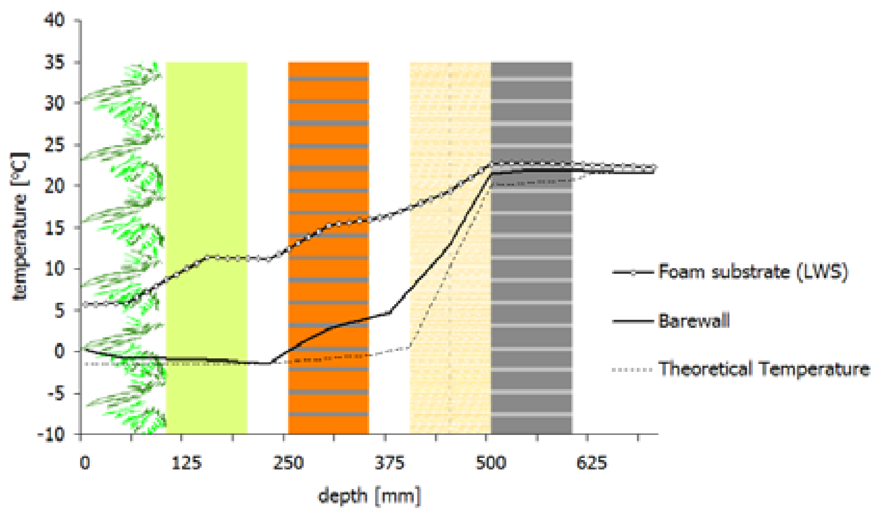

Figure 5.79 Temperature development after 24 hours of cooling, for a bare wall compared with a living wall system based on foam substrate; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

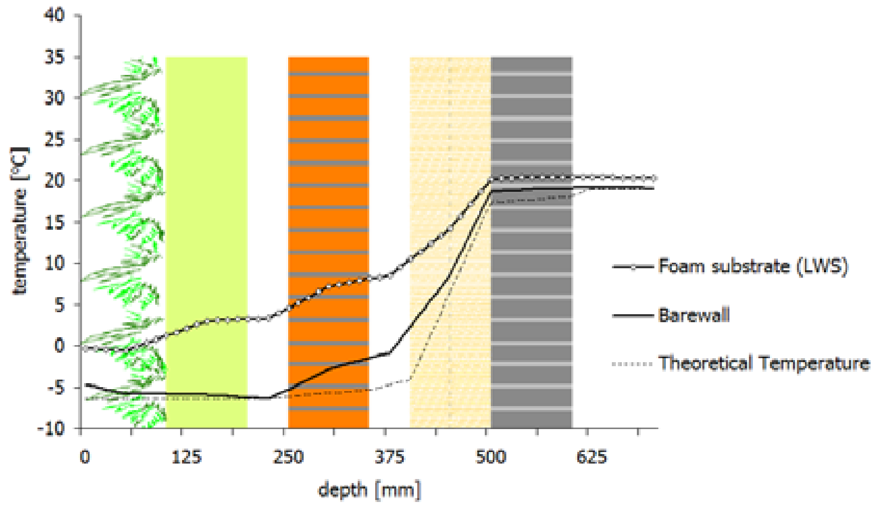

Figure 5.80 Temperature development after 48 hours of cooling, for a bare wall compared with a living wall system based on foam substrate; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

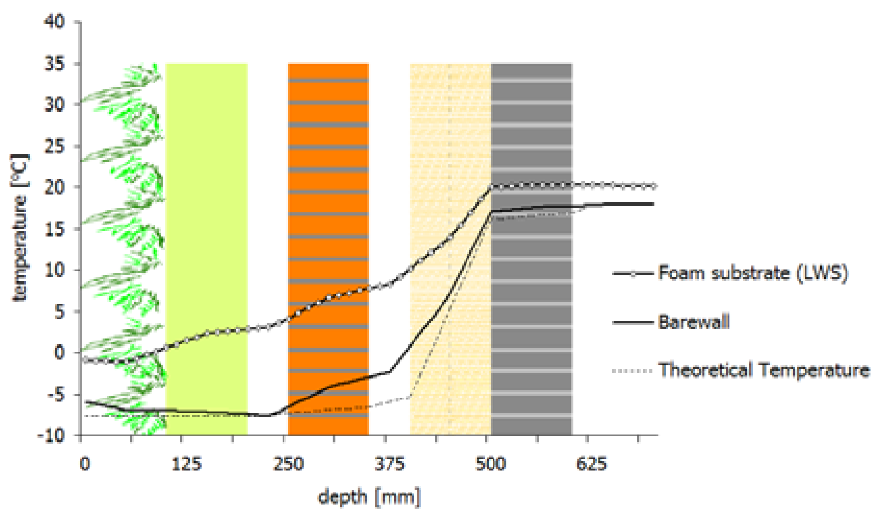

Figure 5.81 Temperature development after 72 hours of cooling, for a bare wall compared with a living wall system based on foam substrate; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

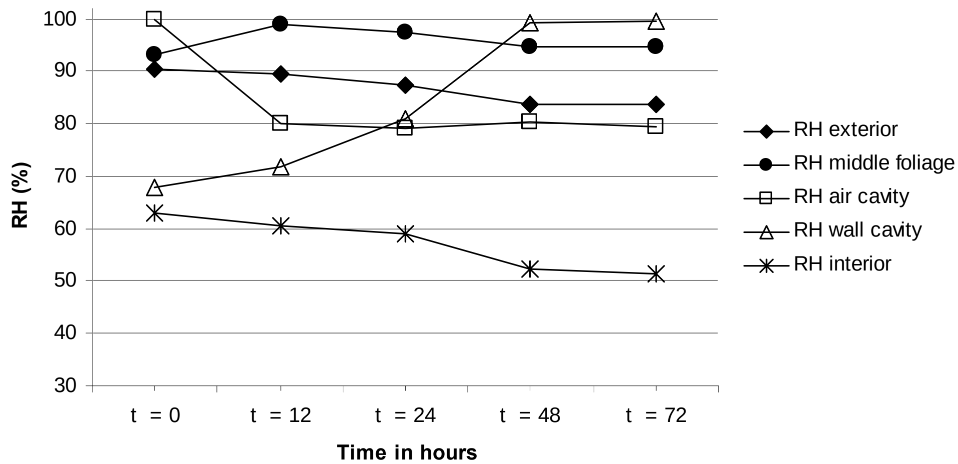

Figure 5.82 Humidity development over different time steps, for a bare wall compared with a living wall system based on foam substrate, given for the winter measurement.

Table 5.22 Summarized data obtained by the thermocouples positioned through the experimental set-up, given for the summer measurement of the living wall system based on foam substrate. Italic lines (t=8 hours) are used for the steady state calculation of the thermal resistance.

Living wall system based on foam substrate											
Time (hours)	measuring points summer temperature (°C)										
	$T_{ext.}$	$T_{green\ surface}$	$T_{middle\ foliage}$	$T_{substrate}$	$T_{air\ cavity}$	$T_{ext.\ wall\ surface}$	T_{cavity}	$T_{surface\ insulation}$	$T_{int.\ surface\ (inside)}$	$T_{int.\ surface\ (outside)}$	$T_{int.}$
$t_{bare\ wall;\ 0}$	*25.28*	--	--	--	--	*24.17*	*24.06*	*23.76*	*23.30*	*23.56*	*24.02*
$t_{mineral;\ 0}$	23.87	23.87	20.02	18.66	17.41	19.14	19.59	19.99	22.51	22.45	22.40
$t_{bare\ wall;\ 1}$	*34.25*	--	--	--	--	*26.22*	*24.73*	*24.47*	*23.75*	*24.01*	*24.02*
$t_{mineral;\ 1}$	30.25	30.25	25.12	21.43	18.44	19.71	19.71	20.10	22.58	22.53	22.45
$t_{bare\ wall;\ 2}$	*34.98*	--	--	--	--	*27.62*	*26.06*	*25.58*	*23.84*	*24.01*	*24.02*
$t_{mineral;\ 2}$	30.92	30.92	26.37	22.64	19.13	20.20	20.06	20.37	22.57	22.52	22.30
$t_{bare\ wall;\ 4}$	*34.50*	--	--	--	--	*30.02*	*28.31*	*27.49*	*24.11*	*24.01*	*24.02*
$t_{mineral;\ 4}$	31.57	31.57	27.45	24.20	20.51	21.32	21.05	21.22	22.62	22.58	22.30
$t_{bare\ wall;\ 8}$	*34.84*	--	--	--	--	*32.63*	*31.29*	*30.10*	*24.54*	*24.25*	*24.13*
$t_{mineral;\ 8}$	32.31	32.31	28.91	26.47	22.52	23.47	23.17	23.03	22.94	22.84	22.58

Table 5.23 Summarized data obtained by the thermocouples positioned through the experimental set-up, given for the winter measurement of the living wall system based on foam substrate. Italic lines (t=72 hours) are used for the steady state calculation of the thermal resistance.

Living wall system based on foam substrate											
Time (hours)	measuring points winter temperature (°C)										
	$T_{ext.}$	$T_{green\ surface}$	$T_{middle\ foliage}$	$T_{substrate}$	$T_{air\ cavity}$	$T_{ext.\ wall\ surface}$	T_{cavity}	$T_{surface\ insulation}$	$T_{int.\ surface\ (inside)}$	$T_{int.\ surface\ (outside)}$	$T_{int.}$
$t_{bare\ wall;\ 0}$	*24.16*	--	--	--	--	*24.43*	*24.40*	*24.32*	*23.44*	*23.98*	*23.49*
$t_{mineral;\ 0}$	20.53	20.53	19.17	19.20	19.32	21.45	21.51	21.59	23.39	23.47	22.99
$t_{bare\ wall;\ 12}$	*2.61*	--	--	--	--	*5.20*	*10.93*	*12.98*	*23.24*	*23.37*	*22.95*
$t_{mineral;\ 12}$	8.67	8.67	8.60	11.92	14.96	16.10	20.06	20.77	23.24	23.37	22.95
$t_{bare\ wall;\ 24}$	*0.20*	--	--	--	--	*0.12*	*4.73*	*7.50*	*21.54*	*21.85*	*21.58*
$t_{mineral;\ 24}$	5.68	5.68	5.81	8.58	11.15	12.37	16.39	17.41	22.64	22.63	22.25
$t_{bare\ wall;\ 48}$	*-4.74*	--	--	--	--	*-5.27*	*-0.82*	*2.35*	*19.61*	*19.07*	*19.07*
$t_{mineral;\ 48}$	-0.37	-0.37	-0.56	1.22	3.32	4.52	8.56	10.45	20.15	20.43	20.58
$t_{bare\ wall;\ 72}$	*-7.62*	--	--	--	--	*-6.64*	*-2.35*	*0.81*	*17.05*	*17.65*	*17.85*
$t_{mineral;\ 72}$	-0.88	-0.88	-1.14	0.59	3.11	4.12	8.24	10.14	19.98	20.29	20.42

5.5.6 Measuring Living Wall System; based on felt layers with pockets


Figure 5.83 Several thin layers of felt are used to let grow plants. From the PVC sheet the layers are: 2 mm of synthetic textile felt, 5 mm felt of non woven fabric made of restructured recycled fibres, 0.1 mm perforated plastic sheet and 2 mm of black synthetic textile felt.The plants are planted in created pockets by cutting the outer felt layer (2mm sheet of black synthetic textile). Plants used are Hedera helix and Pachysandra.

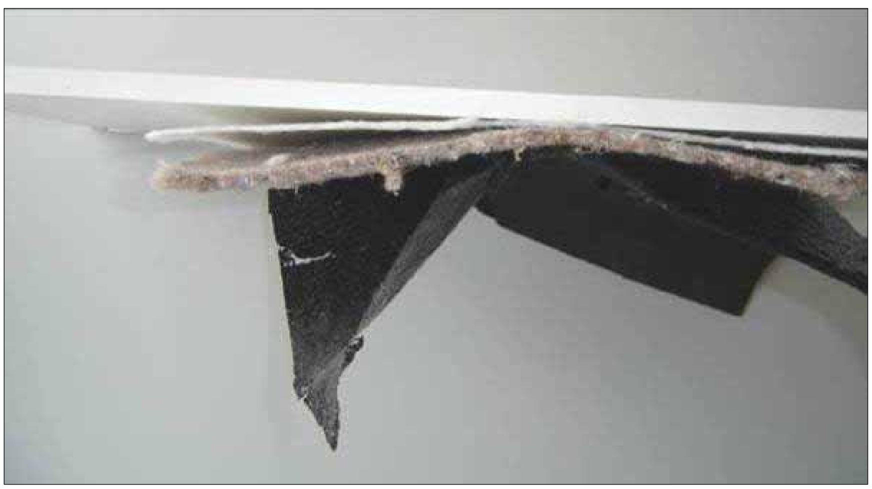

Figure 5.84 cross section of a living wall system based on felt layers as substrate. Characteristic for these living wall systems are the minimum construction thickness (2 cm).

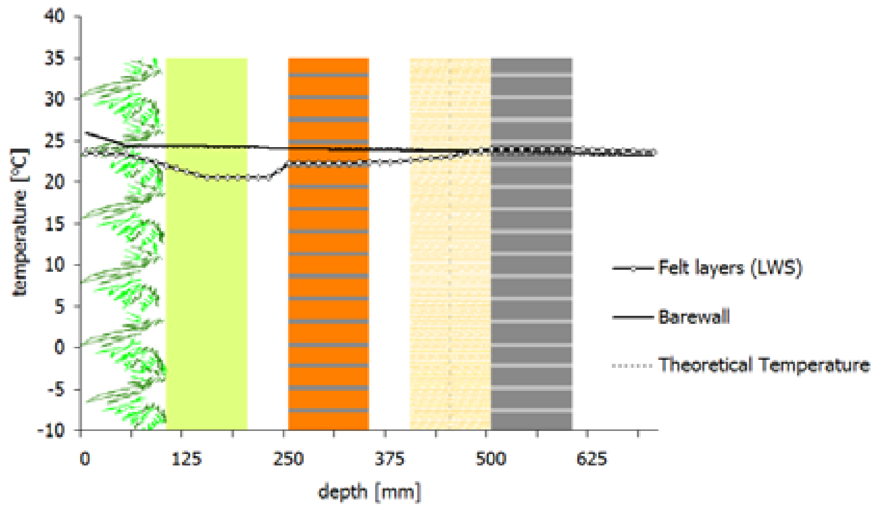

Figure 5.85 Temperature development at the beginning of the summer measurement, for a bare wall compared with a living wall system based on felt layers; t=0 hour.

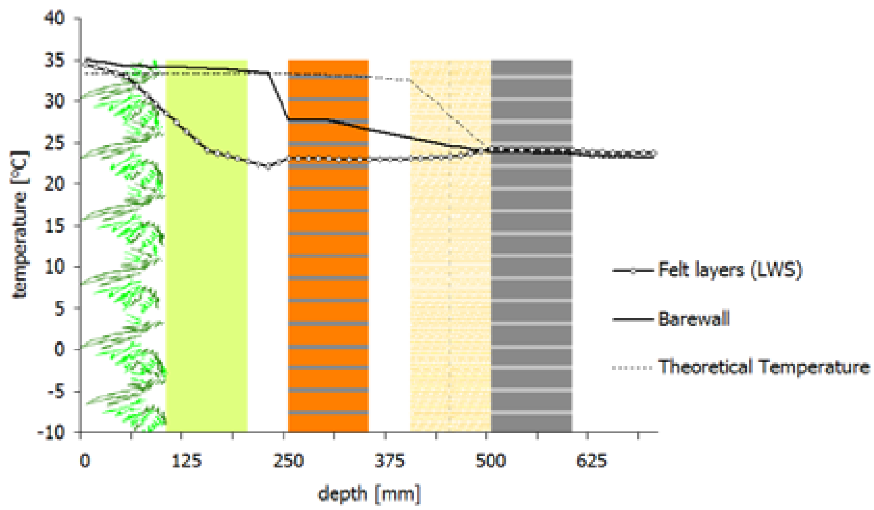

Figure 5.86 Temperature development after 2 hours of heating (35 °C), for a bare wall compared with a living wall system based on felt layers; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

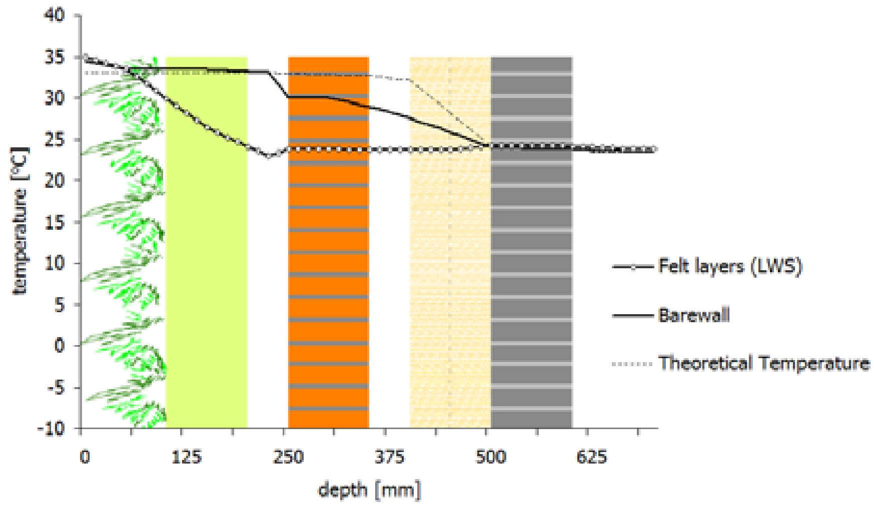

Figure 5.87 Temperature development after 4 hours of heating (35 °C), for a bare wall compared with a living wall system based on felt layers; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

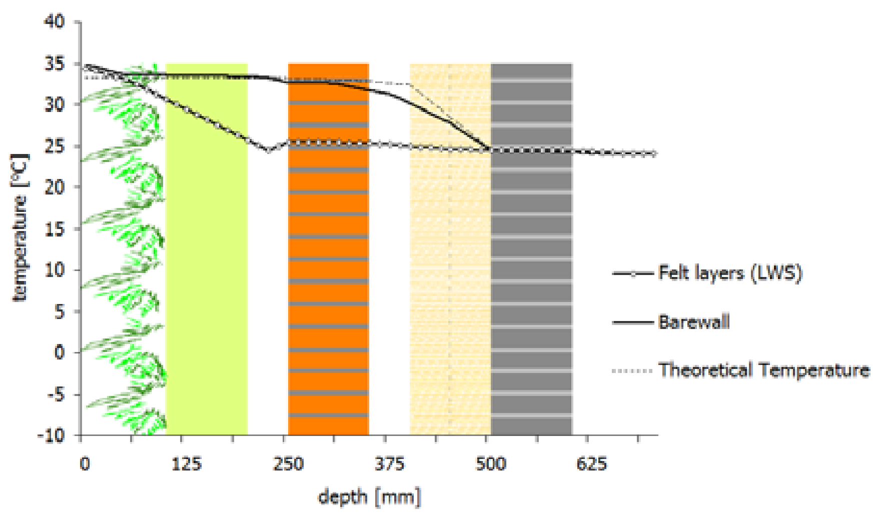

Figure 5.88 Temperature development after 8 hours of heating (35 °C), for a bare wall compared with a living wall system based on felt layers; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

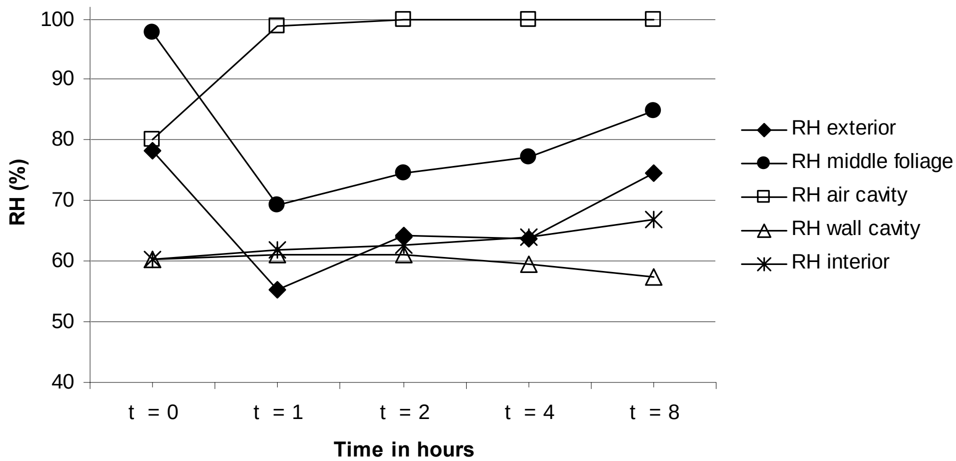

Figure 5.89 Humidity development over different time steps, for a bare wall compared with a living wall system based on felt layers, given for the summer measurement.

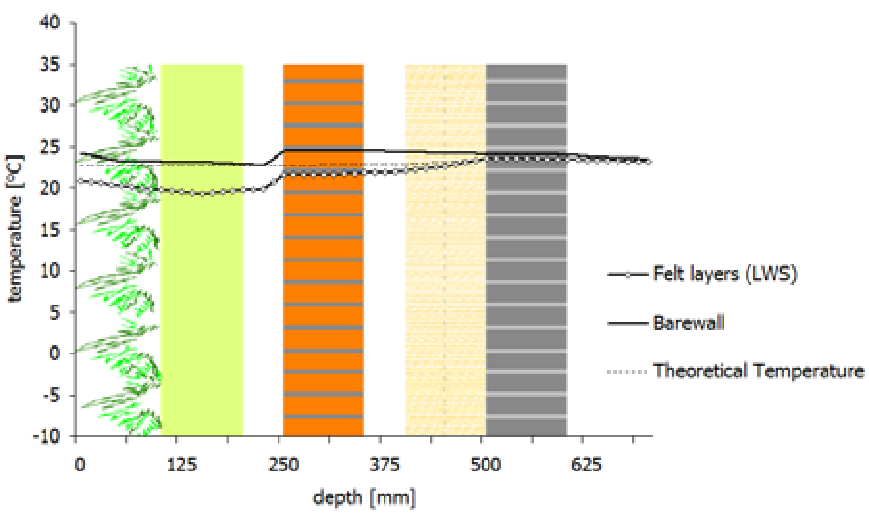

Figure 5.90 Temperature development at the beginning of the winter measurement, for a bare wall compared with a living wall system based on felt layers; t=0 hour.

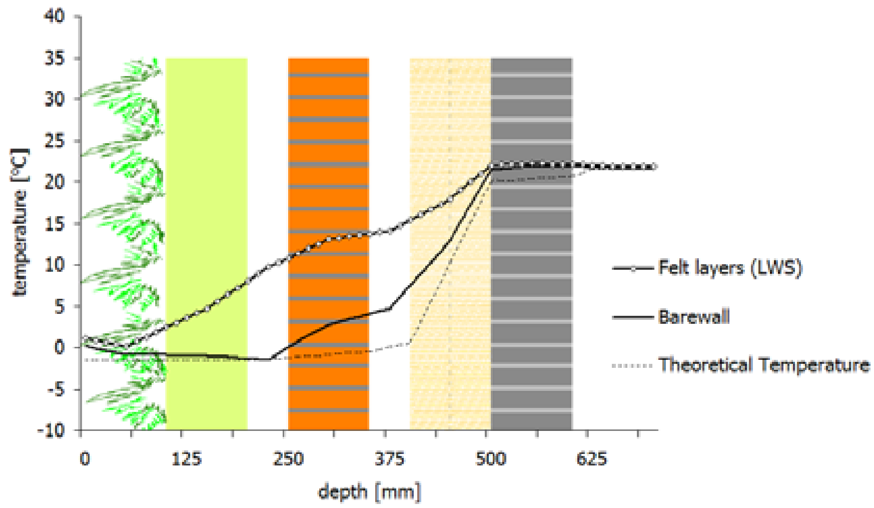

Figure 5.91 Temperature development after 24 hours of cooling, for a bare wall compared with a living wall system based on felt layers; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

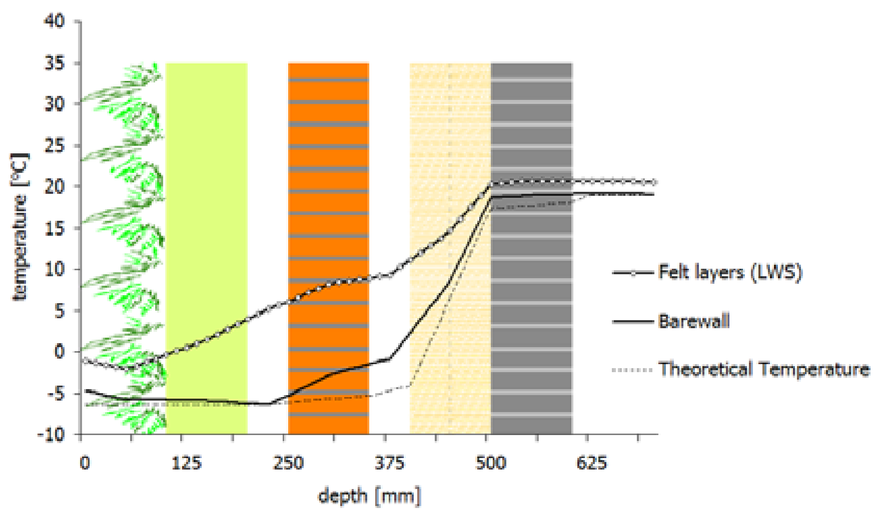

Figure 5.92 Temperature development after 48 hours of cooling, for a bare wall compared with a living wall system based on felt layers; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

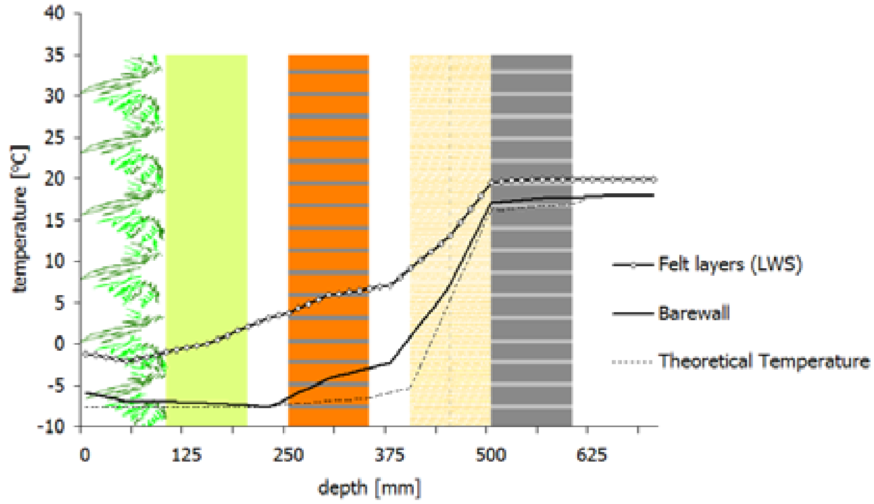

Figure 5.93 Temperature development after 72 hours of cooling, for a bare wall compared with a living wall system based on felt layers; Theoretical line is based on the prevailing temperature to predict a steady state situation for the bare wall.

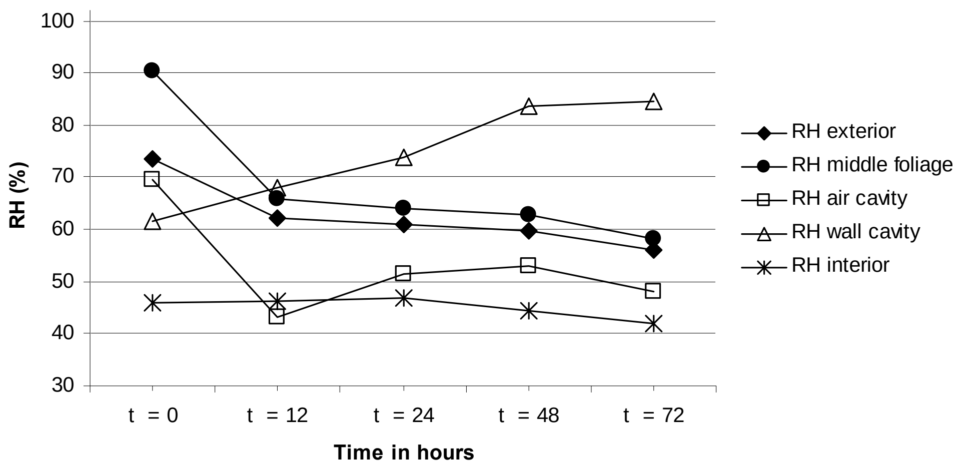

Figure 5.94 Humidity development over different time steps, for a bare wall compared with a living wall system based on felt layers, given for the winter measurement.

Table 5.24 Summarized data obtained by the thermocouples positioned through the experimental set-up, given for the summer measurement of the living wall system based on felt layers. Italic lines (t=8 hours) are used for the steady state calculation of the thermal resistance.

Living wall system based on felt layers											
Time (hours)	measuring points summer temperature (°C)										
	$T_{ext.}$	$T_{green\ surface}$	$T_{middle\ foliage}$	$T_{substrate}$	$T_{air\ cavity}$	$T_{ext.\ wall\ surface}$	T_{cavity}	$T_{surface\ insulation}$	$T_{int.\ surface\ (inside)}$	$T_{int.\ surface\ (outside)}$	$T_{int.}$
$t_{bare\ wall;\ 0}$	*25.28*	--	--	--	--	*24.17*	*24.06*	*23.76*	*23.30*	*23.56*	*24.02*
$t_{mineral;\ 0}$	24.94	24.94	24.12	22.37	20.46	22.17	22.39	22.61	23.66	23.96	23.64
$t_{bare\ wall;\ 1}$	*34.25*	--	--	--	--	*26.22*	*24.73*	*24.47*	*23.75*	*24.01*	*24.02*
$t_{mineral;\ 1}$	32.15	32.15	32.15	27.18	21.38	22.67	22.64	22.82	23.81	24.01	24.02
$t_{bare\ wall;\ 2}$	*34.98*	--	--	--	--	*27.62*	*26.06*	*25.58*	*23.84*	*24.01*	*24.02*
$t_{mineral;\ 2}$	34.50	34.50	33.39	28.53	22.06	23.03	22.91	23.04	24.45	24.11	24.02
$t_{bare\ wall;\ 4}$	*34.50*	--	--	--	--	*30.02*	*28.31*	*27.49*	*24.11*	*24.01*	*24.02*
$t_{mineral;\ 4}$	34.94	34.94	33.07	29.92	22.98	23.79	23.65	23.66	24.13	24.13	24.02
$t_{bare\ wall;\ 8}$	*34.84*	--	--	--	--	*32.63*	*31.29*	*30.10*	*24.54*	*24.25*	*24.13*
$t_{mineral;\ 8}$	34.83	34.83	33.25	30.57	24.46	25.43	25.16	24.94	24.54	24.25	24.13

Table 5.25 Summarized data obtained by the thermocouples positioned through the experimental set-up, given for the winter measurement of the living wall system based on felt layers. Italic lines (t=72 hours) are used for the steady state calculation of the thermal resistance.

Living wall system based on felt layers											
Time (hours)	measuring points winter temperature (°C)										
	$T_{ext.}$	$T_{green\ surface}$	$T_{middle\ foliage}$	$T_{substrate}$	$T_{air\ cavity}$	$T_{ext.\ wall\ surface}$	T_{cavity}	$T_{surface\ insulation}$	$T_{int.\ surface\ (inside)}$	$T_{int.\ surface\ (outside)}$	$T_{int.}$
$t_{bare\ wall;\ 0}$	*24.16*	--	--	--	--	*24.43*	*24.40*	*24.32*	*23.44*	*23.98*	*23.49*
$t_{mineral;\ 0}$	20.87	20.87	20.25	19.77	19.89	21.61	21.90	22.15	23.38	23.45	23.24
$t_{bare\ wall;\ 12}$	*2.61*	--	--	--	--	*5.20*	*10.93*	*12.98*	*23.24*	*23.37*	*22.95*
$t_{mineral;\ 12}$	3.89	3.89	2.81	3.94	13.22	14.12	17.98	18.85	22.90	23.10	22.95
$t_{bare\ wall;\ 24}$	*0.20*	--	--	--	--	*0.12*	*4.73*	*7.50*	*21.54*	*21.85*	*21.58*
$t_{mineral;\ 24}$	1.08	1.08	0.14	2.44	9.69	10.77	14.10	15.40	22.02	21.85	21.58
$t_{bare\ wall;\ 48}$	*-4.74*	--	--	--	--	*-5.27*	*-0.82*	*2.35*	*19.61*	*19.07*	*19.07*
$t_{mineral;\ 48}$	-1.11	-1.11	-2.04	-0.36	5.22	6.05	9.31	11.08	20.30	20.67	20.53
$t_{bare\ wall;\ 72}$	*-7.62*	--	--	--	--	*-6.64*	*-2.35*	*0.81*	*17.05*	*17.65*	*17.85*
$t_{mineral;\ 72}$	-1.20	-1.20	-2.07	-1.05	3.14	3.74	7.07	9.09	19.54	19.90	20.06

5.5.7 Analysis and discussion of measuring different vertical greening systems

Introduction

The average temperature of the air, wall and substrate for the bare wall and for the six greening principles are analyzed and discussed according to the previous paragraphs (5.5.1 – 5.5.6). The values shown in the accompanying tables and figures are the average of several thermocouples readings placed within each vertical greening system and the bare wall. The summer measurements (heating) are carried out for 8 hours a day for safety reasons (laboratory protocol), whereas the winter experiment was conducted over a longer period of 72 hours.

Both the plants and the substrates increase the *R-value* of the building component, which is beneficial for the thermal behaviour of the building and can result in energy cost savings. The objectives of this experimental study are:

- To identify the benefits of vertical greening systems in reducing the heat transfer into the building.
- To examine quantitatively the effect of the six tested vertical greening systems on the (increase) of thermal resistance of the building.
- To compare the abilities of vertical greening systems in lowering temperatures of the façade regarding the urban heat island effect.

1. Direct façade greening

For the direct greening system, it was found that for the summer condition the average temperature of the wall surface is lower compared to the bare wall, with a temperature difference reaching 1.7 °C after 8 hours of heating. The insulation material inside the bare wall moderates the prevailing temperature difference between the exterior and interior climate chamber, resulting in no temperature difference for the interior climate chamber. The humidity profile shows that the initial humidity of the air, inside the exterior climate chamber started from 94% (43% for the interior chamber), this high humidity level is probably caused by placing already vegetation inside the climate chamber and starting next day with measurements. When the relative humidity increases at a constant temperature, it means that the water (vapour) content of the air increases, the more water is in the air the more energy is required for heating up that air.

The humidity decreases rapidly during heating till 75% after two hours, whereas it started to increase again to 100% after 8 hours of heating. The humidity inside the interior chamber is increasing from 43% till 57% over the measurement.

The winter measurement shows that after 72 hours the wall surface covered directly with *Hedera helix* is warmer compared to the bare wall, with a temperature difference of 1.7 °C. The interior air temperature is lowered with 0.7 °C in the case of the bare wall, which means that the vegetation layer slows down the rate of heat flow through the façade resulting in a improved *R-value* of the system. The humidity decreases in time from 65% to 53% for the exterior climate chamber and from 55% to 35% for the interior chamber whereas the humidity inside the air cavity of the wall increases from 48% to 98%.

2. Indirect façade greening

For the indirect greening system, it was found that for the summer condition the average temperature of the wall surface is lower compared to the bare wall, with a temperature difference reaching 1.9 °C after 8 hours of heating. It was observed that the insulation material inside the bare wall moderates the prevailing temperature difference between the exterior and interior climate chamber, resulting in no temperature difference for the interior climate chamber. The humidity increases inside the exterior climate chamber and inside the air cavity between the vegetation and the wall from 70% to 85%. The interior chamber humidity is less affected and increases from 50% to 55%, whereas the humidity of the air cavity of the wall decreases from 50% to 46%.

The winter measurement shows that after 72 hours the wall surface covered indirectly with *Hedera helix* is warmer compared to the bare wall, with a temperature difference of 1.9 °C. The interior air temperature is lowered with 1 °C in the case of the bare wall, which means that again the vegetation layer slows down the rate of heat flow through the façade resulting in an improved *R-value* of the system. The humidity decreases in time from 70% to 50% for the exterior climate chamber, whereas the air cavity of the wall increases from 50% to 100%.

3. Living wall system based on planter boxes

For the planter boxes system (LWS), it was found that for the summer condition the average temperature of the wall surface is lower compared to the bare wall, with a temperature difference reaching 5.8 °C after 8 hours of heating. This is a substantial difference with the direct and indirect greening system. Also for the living wall system based on planter boxes it was noticed that the insulation material inside the bare wall moderate the prevailing temperature difference between the exterior and interior climate chamber, resulting in no temperature difference for the interior climate chamber. It is noteworthy to mention that the temperature difference between the air of the exterior chamber and the temperature of the extra created air cavity between LWS and façade was 8.6 °C. It was noticed that the humidity inside the exterior climate chamber lays between 85% and 100% for the measurement; this is probably related to the moisture content of the substrates used for the living wall systems. The humidity inside the interior climate increases from 60% to 73%, whereas it decreases inside the air cavity of the wall from 60% to 56%.

The winter measurement shows after 72 hours a temperature difference between the surface of the bare wall and the wall covered with planter boxes of 10.6 °C, with a temperature difference between the exterior air temperature and the extra created cavity of 5.5 °C. The interior air temperature difference after the measurement came up 2.1 °C and thus resulting in an improved *R-value* of the system.
The humidity decreases in time from +/- 85% to 57% for the cavity between planter box and façade, whereas the air cavity of the wall increases from 60% to 95%.

4. Living wall system based on mineral wool
For the living wall system based on mineral wool (LWS), it was found that for the summer condition the average temperature of the wall surface is lower compared to the bare wall, with a temperature difference reaching 8.4 °C after 8 hours of heating. The air temperature difference between the exterior chamber and the air temperature of the extra created air cavity between LWS and façade was 8.4 °C. For the humidity development the same trend was found as for the living wall base on planter boxes. Due to the high moisture content of the substrate a high humidity was found during the measurement for the exterior climate chamber. The humidity inside the interior climate chamber rises from 45% to 55%.
The winter measurement shows a temperature difference after 72 hours between the surface of the bare wall and the wall covered with mineral wool of 10.6 °C, with a temperature difference between the exterior air temperature and the extra created cavity of 4.6 °C. The interior chamber air temperature difference after 72 hours came up 2.1 °C and thus resulting also in an improved *R-value* of the system. The humidity level of the interior chamber was more or less constant of the measurement (+/- 40%), the same as for the exterior chamber (+/- 65%), whereas the air cavity of the wall increases from 65% to 94%.

5. Living wall system based on aminoplast foam
For the living wall system based on mineral wool (LWS), it was found that for the summer condition the average temperature of the wall surface is lower compared to the bare wall, with a temperature difference reaching 9.2 °C after 8 hours of heating. The air temperature difference between the exterior chamber and the air temperature of the extra created air cavity between LWS and façade was 9.8 °C. Again the insulation material inside the bare wall moderates the prevailing temperature difference between the exterior and interior climate chamber, resulting in no temperature difference for the interior climate chamber. High humidity levels are found during the measurement for the exterior chamber. The humidity level decreases inside the air cavity (from 68% to 62% of the wall whereas it increases for the interior chamber from 53% to 62%.
The winter measurement shows a exterior surface temperature difference between the bare wall and the wall covered with aminoplast foam substrate of

10.8 °C and a difference of 4 °C between the exterior air temperature and the air temperature inside the extra created cavity between living wall and façade. The interior chamber air temperature difference after 72 hours came up 2.1 °C and thus resulting again in an improved *R-value* of the system. During the measurement high humidity levels were observed for the exterior chamber whereas the humidity level decreases for the interior chamber.

6. Living wall system based on felt layers

For the living wall system based on felt layers (LWS), it was found that for the summer condition the average temperature of the wall surface is lower compared to the bare wall, with a temperature difference reaching 7.2 °C after 8 hours of heating. This fits well with the other living wall concepts compared to the direct and indirect greening system were lower temperature differences were found. The air temperature difference between the exterior chamber and the air temperature of the extra created air cavity between LWS and façade was 10.3 °C. During the experiments, the same trend was found for the insulation material (inside the cavity wall), it moderates the prevailing temperature difference substantially between the exterior and interior climate chamber, resulting in no temperature difference for the interior climate chamber. Again high humidity levels were found during the measurement inside the exterior climate chamber. Again it was observed that the humidity of the interior chamber increases (60% to 68%) whereas the humidly decreases from 60% to 57% for the air cavity inside the wall. The winter measurement shows a surface temperature difference between the bare wall and the wall covered with felt layers of 10.4 °C and a difference of 4.3 °C between the exterior air temperature and the air temperature inside the extra created cavity between living wall and façade. The interior chamber air temperature difference between the bare wall and the covered wall after 72 hours came up 2 °C, resulting again in an improved *R-value* of the system. During the measurement high humidity levels were observed for the exterior chamber whereas the humidity level decreases for the interior chamber. The humidity level of the air cavity inside wall increases from 60% to 85%.

Estimation of the thermal resistances and a critical analysis of the data obtained from the climate chamber

The conducted experiment allows studying the thermal behaviour with respect to the R-value of the green (series) systems as discussed in paragraph 5.2. The estimation of equivalent R-values of the six vertical greening systems, was based on the data collected in the experimental climate chamber, using the measured interior and exterior surface temperatures, both for a summer and winter situation. Both situations are valuable to understand the interaction of the vegetation with respect to the thermal behaviour of the systems as tested inside the climate chamber better. The summer measurements are conducted over a time span of 8 hours where it is assumed to reach a steady state situation. The winter measurements are conducted over a larger time span of 72 hours, where it is supposed to be (really) steady state. For steady state conditions, the rate of heat flow per unit area through the bare façade; direct and indirectly greened, can be estimated according to equations 7 and 9 (paragraph 5.2). For the living wall concepts equations 8 and 10 are used (paragraph 5.2), the equations are derivate according to figure 5.6. The summarized R-values based on the summer and winter measurement can be found respectively in table 5.26 and table 5.27.

Table 5.26 Estimated R-values for the greening systems tested under summer condition; assuming a steady state situation after 8 hours of heating. The values given in grey (regarding the living wall systems) must be considered as not reliable due to the high values, apparent a steady state situation was not arisen.

summarized thermal resistances summer measurement	
Vertical greening systems	*R-value (W/m^2)*
Bare wall	3.43
Hedera helix direct (based on paragraph 5.5.1)	0.66
Hedera helix indirect (based on paragraph 5.5.2)	1.10
LWS based on planter boxes (based on paragraph 5.5.3)	*12.81 *)*
LWS based on mineral wool (based on paragraph 5.5.4)	*33.15 *)*
LWS based on aminoplast (based on paragraph 5.5.5)	*47.99 *)*
LWS based on felt layers (based on paragraph 5.5.6)	*27.24 *)*

Table 5.27 Estimated R-values for the greening systems tested under winter condition; assuming a steady state situation after 72 hours of cooling.

Summarized thermal resistances winter measurement	
Vertical greening systems	*R-value (W/m^2)*
Bare wall	3.42
Hedera helix direct (based on paragraph 5.5.1)	0.18
Hedera helix indirect (based on paragraph 5.5.2)	0.18
LWS based on planter boxes (based on paragraph 5.5.3)	1.30
LWS based on mineral wool (based on paragraph 5.5.4)	1.10
LWS based on aminoplast foam (based on paragraph 5.5.5)	1.06
LWS based on felt layers (based on paragraph 5.5.6)	1.05

*) Values are virtually and not representative to calculate with. However they still confirm the positive influence of vertical greening systems on the thermal behaviour of a building.

From the estimation of the R-values regarding the vertical greening systems, it can be concluded that the values obtained for the summer measurement, seems to be unreliable to due to the extreme high R-values calculated. This is probably due to the fact that the measuring time of 8 hours was not sufficient enough to reach a steady state situation for the heat flow through the vertical greening systems, especially for the living wall systems this is the case, due to the high temperature differences between the several layers (vegetation, materials, air, etc.) involved. ***The values presented can not be used for calculations!***

Regarding the equation used (eq. 10), the temperature gradient ΔT_{lws} *(difference between* T_1 *and* T_2*) has a high influence on the outcome of the equation. The larger the temperature drop over the living wall system, the higher the* R_{LWS} *value will be. In the case of the summer measurements after 8 hours heating, still high a high temperature gradient (*T_1-T_3 *up to 10 °C) over the living wall systems was found as earlier described, whereas the temperature gradient over the bare wall (*T_3-T_4*) appeared to be 1.5 °C as a maximum.*

$$R_{LWS} = R_T \frac{(T_1 - T_3)}{(T_3 - T_4)} \qquad (10)$$

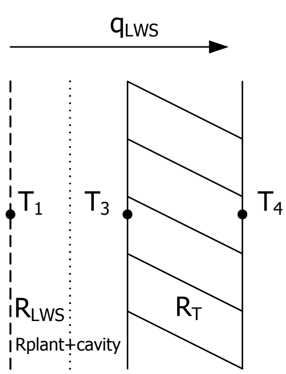

Figure 5.95 Illustration of calculating the heat flow through a façade covered with a living wall system.

Besides it is eventually not clear what the real effect of the moisture content (evapotranspiration; the contribution of vegetation and substrate) on the heat transfer mechanism is inside a closed and sealed environment. It is likely that this mechanism causes the high temperature differences found for the summer measurement. Building materials (abiotic) are tested via the same principle (steady state) according to the standard NEN-EN 1934, the difference with the executed experiment is the introduction of a (unknown) biological factor, a factor that was more or less aimed to identify. Another comment that has to be drawn is the fact that in practice the (exterior climate chamber) humidity levels are affected due to ventilation by wind. Interior humidity levels are mostly influenced by the use of a building (human activity, cooking, etc.).

From the summer measurements however, can be seen that there is a considerable effect in reducing the temperature development in the exterior masonry by applying vertical greening systems, in particular for the living wall concepts. This means that less heat accumulation will occur in a vertical greened façade in daytime, resulting in less heat radiation at night and thus mitigates the urban heat island effect based on the obtained data substantially. The estimation of the *R-values* regarding the winter measurement presented in table 5.27 are apparent lower compared to the summer measurement. As mentioned before the measuring time of 72 hours tend to be steady state compared with a measuring time of 8 hours. Another important aspect is the evaporative character of the vertical greening systems under colder temperatures (frost) which is less compared to the summer measurement were the plants (+substrate) are constantly (evapo)transpirate to fulfil their biological functions. Again it is observed that the greening systems influence positively the temperature development through the façade. This indicates that the thermal resistance (table 5.27) of the construction is improved by adding a green layer.

The designed experimental set-up was based on symmetrical climate chambers (indoor and outdoor) with limited sizes to reduce the amount of energy needed for each test. The typical bare brick wall used for this experiment intends to show the difference in the thermal behaviour of adding vertical greening systems on the whole (series) system. According to the results obtained, the hotbox acts wherefore it was designed; differences are found between the bare wall and between different vertical greening systems. The thermal behaviour of the bare wall corresponds with the theoretical calculations based on the measured temperatures and the thermal conductivities of the used materials. When vertical greenery is involved (and their evapotranspiration capacity) the more energy is consumed, this process contributes substantially to the cooling potential and thus automatically leads to a higher *R-value* found for the vertical greening systems.

As overall conclusion can be said that the *R-values* obtained from the summer measurement are not reliable to calculate with, due to the high values found. The evaporation and the fact that water (vapour) can not escape from the sealed chambers causes the high temperature difference after 8 hours (water accumulates heat). To obtain more realistic results regarding the *R-value* of the greening systems, an improvement of the climate chamber, could be to enlarge the volume of the exterior chamber (side where the greenery is placed) this to lower the influence of evaporation (asymmetrical chambers). Since an increase of the air volume means that more vapour could be taken up by the air.

However from field measurements (paragraph 5.4) smaller surface temperatures differences are found between bare and greened façades, mostly with an ambient air temperature between 20-25 °C. The measurements inside the climate chamber are conducted under a higher boundary condition of 35 °C (chosen to highlight temperature differences), the temperatures difference found in the designed climate chamber, between a bare and greened wall are therefore enlarged and in accordance with the trend found by field measurements.

The measurements are carried out on 1 m^2 façade in the laboratory, to predict the thermal behaviour of the building, one have to take the whole building envelope into account. According to Tilley (2011) the thermal load (interior climate) of a cubic shaped building is mostly influenced by the glass surface compared to the façade surface. This means that most of energy use (cooling and heating) of the building is influenced by the design of the building envelope.

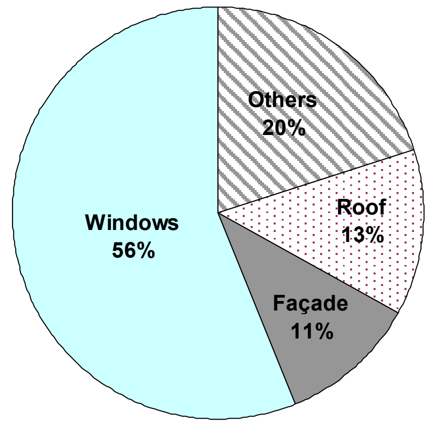

Figure 5.96 Percentages of contribution given for the thermal load for a cubic shaped building according to Tilley, 2011.

Statistical analysis of the temperature measurements

To verify the temperature measurements done in the climate chambers, the bare wall is tested 3 times (Appendix A and B) during the experiment (at the beginning, at the end and after 4 months). Via this procedure the behaviour of the designed apparatus and the bare wall are falsified on there reproducibility of the measurements. Since the bare wall is tested under the same boundary conditions, a Repeated Measures ANOVA (with *p=0.05%*) test is used to identify if there are differences between the three measurements. The null hypotheses tested are:

- $H_{bare\ wall1} = H_{bare\ wall3}$;(p=0.060)
- $H_{bare\ wall2} = H_{bare\ wall3}$;(p=0.634)
- $H_{bare\ wall1} = H_{bare\ wall2}$;(p=0.276)

The results of the statistical analysis show that all the null hypothesises are accepted, there are no significant differences between the conducted measurements of the bare wall.

According to the data obtained from the experiments, a statistical analysis (*t-test*) was performed, between three reference measurements of the bare wall and the single measurements of the greening systems analyzed in this thesis. Inside the statistical analysis a distinction is made between the greening systems according to their classification (direct an indirect versus living wall systems, presented in table 5.28). The probability level used inside the analysis was *p=0.05%.* The hypothesis (H_0) used for the statistical analysis was:

- $H_{0;}$ There is no influence of vertical greening on the temperature gradient through a façade.

Table 5.28 Statistical analysis structure to falsify the null hypothesis.

type	analysis	Greening type
Bare wall	*t-test (p=0.05)*	Direct façade greening Indirect façade greening
3 measurements - at the beginning - at the end - after 4 months	*t-test (p=0.05)*	LWS based on planter boxes LWS based on mineral wool LWS based on foam substrate LWS based on felt layers

The result of the statistical analysis shows:

- Bare wall compared to the direct and indirect greening system both for the summer and winter measurement no statistical differences are found (H_0= accepted).
- Bare wall compared to the living wall systems shows both for the summer and winter measurement a significant difference between the temperatures found (H_0= rejected).

Since the temperature differences between the bare wall, direct and indirect greening system are very small, more data is necessary to have more reliability in the outcome of the analysis. In other words more measurements inside the climate chamber are advisable for the direct and indirect greening type.

6 Sustainability aspects of vertical green

6.1 Introduction

Since the early 1990's, considerable efforts have been made to develop tools that enable users (architects, developers, designers, etc.) to evaluate ecological aspects of sustainable buildings during different design stages (Abu Sa'deh and Luscuere, 2000). The methodology or tools for sustainable building assessments regarding the life cycle of a product or construction can be fulfilled with a so called Life Cycle Assessment (LCA). The essence of life cycle assessments is the examination, identification and evaluation of the relevant environmental implications of a material, process, product, or system across its life span from creation to waste or, preferably, to re-creation in the same or another useful form. 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). A life cycle assessment is a large and complex effort, and there are many variations possible. Nonetheless, there is general agreement on the formal structure of LCA, which contains three stages: goal and scope definition, inventory analysis and interpretation or impact analysis (Greadel, 1990). The outline of the methodology can be given by figure 6.1.

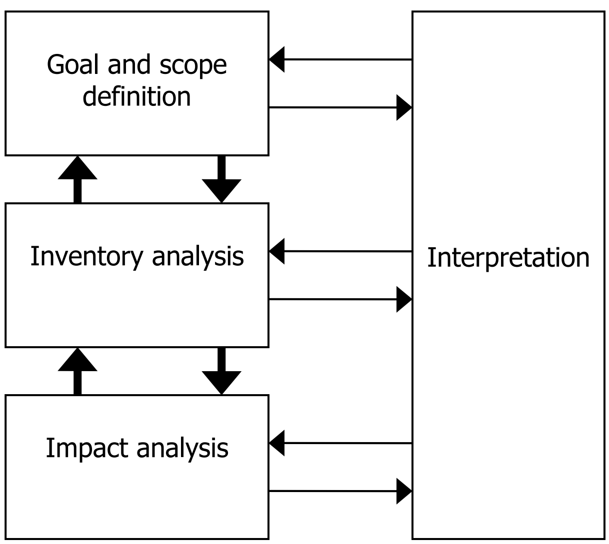

Figure 6.1 Stages in the life cycle assessment. The wide arrows indicate the basic flow of information. At each stage, results are interpreted and thus provide the possibility of revising the environmental attributes of the activity being assessed. Inside the inventory analysis it is important to set a functional unit (Dobbelsteen & Alberts, 2001).

The functional unit describes and quantifies those properties of a product or system which must be present for the studied substitution to take place. The functional unit set in this thesis, is 1 m^2 of a greened façade with vegetation either rooted in the soil or rooted at grade in artificial substrate.

Sustainability has become a key idea in national and international discussions following the publication of the Brundtland Report (1987) and the 1992 Rio 'Earth Summit' (Doughty and Hammond, 2004). Considering the concept of sustainability the building environment is responsible of almost 40% of the global emissions. What can be defined as sustainable or eco-architecture represents an attempt to respond to global environmental problems and to reduce environmental impacts due to the building and housing industry, which include the exhaustion of natural resources, the emission CO_2 and other greenhouse gases (Pulselli et al. 2006). The integration of vegetation on buildings, through green roofs or vertical greening, allows to obtain a relevant improvement of the building's efficiency, ecological and environmental benefits. The benefits gained thanks to the use of vegetation are the subject of studies and researches starting from the seventies (Bellomo, 2003). Green façades and vertical greening concepts offer the potential to learn from traditional architecture, the earliest form of vertical gardens dates from 2000 years ago in Mediterranean region, but also to incorporate advanced materials and other technology to promote sustainable building functions (Köhler, 2008). It is a good example of combining nature and buildings (linking different functionalities) in order to address environmental issues in dense urban surroundings (Bohemen, 2005), since urban centres today are currently searching for areas to plant vegetation, due to the lack of space.

Beside the environmental benefits of vertical greening systems (a lot of the benefits are still subject of intensive research around the world), it is eventually not clear if these vertical greening concepts (all or some) are sustainable, due to the materials used, maintenance, nutrients and water needed. Paragraph 6.2 intents to give more insight in the sustainability aspect of vertical greening systems. The study regards traditional façade greening (direct and indirect; rooted in the soil) and modern façade greening by applying living wall systems. Due to the variety on the market nowadays in different living wall concepts, only two complete different LWS concepts are studied in the presented life cycle analysis.

6.2 Comparative life cycle analysis for green façades and living wall systems

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M. Ottelé[1], K. Perini[2], A.L.A. Fraaij[1], E.M. Haas[1,3], R. Raiteri[2]
[1] Faculty of Civil Engineering and Geosciences, Delft University of Technology
Stevinweg 1, 2628 CN Delft, P.O. Box 5048, The Netherlands.
[2] Faculty of Architecture, University of Genoa
Stradone S. Agostino, 37 - 16123 Genoa, Italy
[3] Dutch Institute for Building Biology and Ecology (NIBE)
Bussummergrindweg 1b, 1406 NZ Bussum
Corresponding authors: M.Ottele@tudelft.nl, katiaperini@hotmail.com

Abstract
Greening the building envelope focusing on green façades with vegetation is a good example of a new construction practice. Plants and partly growing materials in case of living wall systems (LWS) have a number of functions that are beneficial, for example: increasing the biodiversity and ecological value, mitigation of urban heat island effect, outdoor and indoor comfort, insulating properties, improvement of air quality and of the social and psychological well being of city dwellers.
This paper discusses a comparative life cycle analysis (LCA) situated in The Netherlands for: a conventional built up European brick façade, a façade greened directly, a façade greened indirectly (supported by a steel mesh), a façade covered with a living wall system based on planter boxes and a façade covered with a living wall system based on felt layers. Beside the environmental benefits of the above described greening systems, it is eventually not clear if these systems are sustainable, due to the materials used, maintenance, nutrients and water needed. A LCA is used to analyze the similarity and differences in the environmental impacts in relation with benefits estimated for two climate types (temperate and Mediterranean), already quantified in former researches, for building energy saving (reduction of electrical energy used for building cooling and heating).

Keywords: façade greening, living wall systems, LCA (life cycle analysis), sustainability, environmental burden, environmental benefits.

Introduction

Background

Vegetation can be seen as an additive (construction) material to increase the (multi)functionality of façades of buildings. 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 (www.greenroofs.org). Vertical green is the result of greening vertical surfaces with plants, either rooted into the ground, in the wall material itself or in modular panels attached to the façade in order to cover buildings with vegetation and can be classified into façade greening and living walls systems (Dunnett and Kingsbury, 2004; Köhler, 2008).

Greening the cities is not a new approach (i.e. hanging gardens of Babylon), but the benefits are rarely quantified. Greening façades is a good example of combining nature and buildings (linking different functionalities) in order to address environmental issues in dense urban surroundings (van Bohemen, 2005). The main benefits due to the use of green façades applications are of economical, social and environmental origin such as greenhouse gas (emission) reduction, adaptation to climate change, air quality improvements, energy saving by insulation, habitat provision and improved aesthetics (Minke, 1982; Krusche et al 1982; Peck, S.W. et al, 1999). Also sound reduction is possible by the use of vegetation (Pal et al, 2000).

Vertical greening concepts can be divided into categories (green façades and living wall systems) according to their growing method. Green façades are based on the use of climbers (evergreen or deciduous) attached themselves directly to the building surface (as in traditional architecture), or supported by steel cables or trellis. In the first case climbers planted in the ground at the base of the building allows to obtain a cheap façade greening but there could be implications for any building works that needed to be carried out (for example damages and maintenance of the façade), besides that climbing plants can only grow to a maximum of 25 m height and it can take several years (Dunnet and Kingsbury, 2004). Supporting systems are sometimes necessary and planter boxes, such as prefabricated and prevegetated systems (living wall systems), attached to walls can require specific growing substrate to facilitate plant growth. Living wall systems (LWS) consists of modular panels, each of which contains its own soil or other growing medium (soil, felt, perlite, etc) based on hydroponic culture, that is using balanced nutrient solutions to provide all or a part of the plant's food and water requirements (Dunnet and Kingsbury, 2004).

Aim of the research

The goal of this life cycle analysis (LCA) is to evaluate the actual and potential environmental aspects associated with constructing, maintaining and disposing of 1 m^2 façade and to determine the impact of the raw material depletion, fabrication, transportation, installation, operation, maintenance and waste for four greening systems compared to a bare façade. In addition, a start was made to transform the positive quantifiable aspects of vertical greened surfaces into a lower

environmental impact (due to a reduction of energy savings) during the life span of a greened building.
The presented LCA research, conducted in Delft (The Netherlands), examines a conventional bare built up European brick façade, a conventional façade covered with a climber planted at the base of the façade (greened directly), a conventional façade covered with a climber (planted also at the base of the façade) using a stainless steel framework to create a cavity between foliage and façade (indirectly), a conventional façade covered with a living wall system (LWS) based on planter boxes filled with potting soil and a conventional façade covered with a living wall system based on felt layers.
To develop the LCA model an inventory analysis was created. In this phase information has been collected about the materials involved for the bare wall and the different greening systems. The materials needed were obtained from the project construction documents and information provided by the manufactures.
A life cycle analysis for the four vertical greening systems investigated allows evaluating their sustainability in relation with the achievable environmental benefits, as a measure of ecological quality based on our knowledge of the influence on the environment. Sustainability can be defined as a general property of a material or a product that indicates whether and to what extent the prevailing requirements are met in specific application. These requirements, which relate to air, water and soil loading, have influences on well being and health of living creatures, the use of raw materials and energy, and also consequences for the landscape, the creation of waste and the occurrence of nuisance to surrounding environment (Hendriks et al, 2000).

Ecological and environmental benefits.
In recent (and older) literature several claims are done about the positive influence of green façades. Even if green façades have been studied from the eighties, especially by older German literature, still most of the benefits have been only estimated and not quantified.
Living wall systems (LWS) and green façades have different characteristics that can have influence on the benefits like cooling and insulating properties. Relevant aspects are the thickness of the foliage (creating a stagnant air layer and shading the façade), water content, material properties and possible air cavities between the different layers.
Between façade and the dense vertical green layer, both rooted in the soil and rooted in artificial pre-vegetated based systems (hydroponic), a stagnant air layer exist. Stagnant air has an insulating effect; green façades can therefore serve as an "extra insulation" of the building envelope (Minke et al, 1982; Krusche et al, 1982; Perini et al, 2011). Also direct sunlight on the façade is filtered by leaves, thanks also to the phototropism effect. 100% of sun light energy that falls on a leaf, 5-30% is reflected, 5-20% is used for photosynthesis, 10-50% is transformed into heat, 20-40% is used for evapotranspiration and 5-30% is passed through the leaf (Krusche et al, 1982). This blocking of the direct sunlight exposure ensures a cooling effect in warmer climates. Secondly, green façades and roofs will cool the heated air through evaporation of water (Wong, et al., 2009); this process is also

known as evapotranspiration. As a consequence every decrease in the internal air temperature of 0.5 °C will reduce the electricity use for air-conditioning up to 8% (Dunnet and Kingsbury, 2004). In winter, the system works the other way and heat radiation of the exterior walls is insolated by evergreen vegetation. In addition, the dense foliage will reduce the wind flow around the façade and thus also helps to prevent the cooling down of the building.

The greening of vertical surfaces has a beneficial effect on the insulating properties of buildings through exterior temperature regulation (Krusche et al, 1982). The role of insulation materials and stagnated air layers is to slow down the rate of heat transfer between the inside and outside of a building, which is a function of the difference between the inside and outside temperatures. The insulation value of vertical greened surfaces can be increased in several ways (Peck et al, 1999):

- By covering the building with vegetation, the summer heat is prevented to reach the building skin, and in the winter, the internal heat is prevented to escape.
- Since wind decreases the energy efficiency of a building by 50%, a plant layer will act as a buffer that keeps wind from moving along a building surface.
- By the materials and substrates used in the case of living wall concepts.

In the beginning of the eighties Krusche et al. (1982) have estimated that the thermal transmittance of a 160 mm plant cover is 2.9 $Wm^{-2}K^{-1}$. Minke et al. (1982) also suggested to reduce the exterior coefficient of heat transfer. By reducing the wind speed along a green façade the exterior surface resistance coefficient can be equalized to the interior surface resistance coefficient as demonstrated by Perini et al (2011). Field measurements on a plant covered wall and a bare wall by Bartfelder and Köhler (1987) show a temperature reduction at the green façade in a range of 2-6 °C compared with a bare wall. Also Eumorfopoulou and Kontoleon (2009) have reported a temperature cooling potential of plant covered walls in a Mediterranean climate; the effect was up to 10.8 °C. Another recent study by Wong et al. (2009) on a free standing wall in Hortpark (Singapore) with vertical greening types shows a maximum reduction of 11.6 °C. Alexandri and Jones (2008) simulated a temperature decrease in a urban canyon with greened façades a reduction of air temperature 4.5 °C for the Mediterranean climate and 2.6 °C for the temperate climate. In research done by Eumorfopoulou and Aravantinos (1998) they concluded that a planted roof contributes to the thermal protection of a building but that it cannot replace the thermal insulation layer.

The integration of vegetation on buildings, through green roofs and vertical greening, allows to obtain also ecological and environmental benefits and increases biodiversity, besides social and aesthetical benefits (Cassinelli and Perini, 2010). The ecological and environmental benefits regard, as for green roofs, the improvement of air quality (Ottelé et al., 2010), energy savings for the building heating and cooling and the reduction of the heat island effect. Greening paved surfaces with vegetation to intercept the radiation can reduce the warming up of hard surfaces, especially in dense urban areas. In the urban area, the impact of evapotranspiration and shading of plants can significantly reduce the amount of heat that would be re-radiated by façades and other hard surfaces. Besides that the green plant layer will also reduce the amount of UV light that will fall on building materials. Since UV light deteriorates the material and mechanical properties of coatings, paints, plastics, etc. plants will also have positive effect on durability aspects and on maintenance costs.

Methodology

Basic approach
In this research, life cycle analysis (LCA) is used to calculate the environmental impact of the production, use, maintenance and waste for four common systems for vertical greening of buildings. This is to compare the environmental burden and benefits of the green system with a bare brick wall (figure 6.2.1):

1. bare wall (brick)
2. direct façade greening system + bare wall
3. indirect façade greening + bare wall
4. living wall system (LWS) based on planter boxes filled with soil + bare wall
5. living wall system (LWS) based on felt layers + bare wall

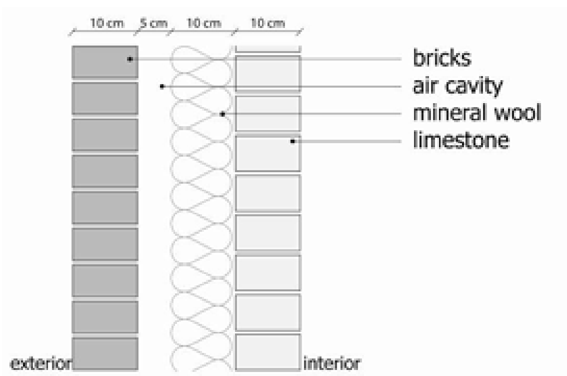


Figure 6.2.1 Bare wall with materials layers.

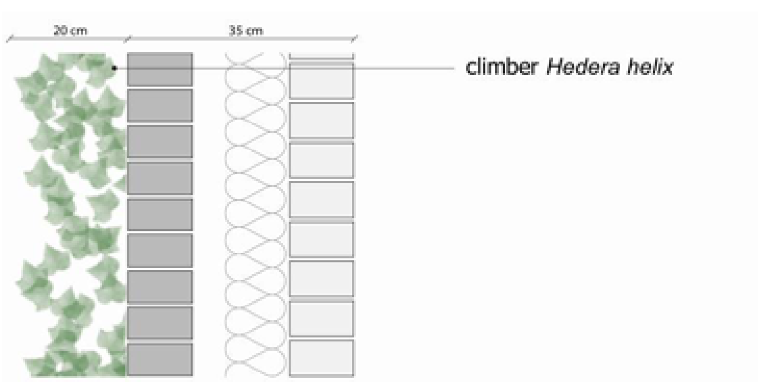


Figure 6.2.2 Direct greening system with materials layers.

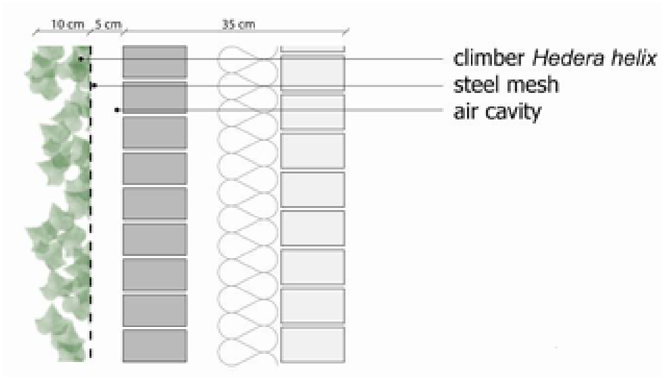


Figure 6.2.3 Indirect greening system with materials layers.

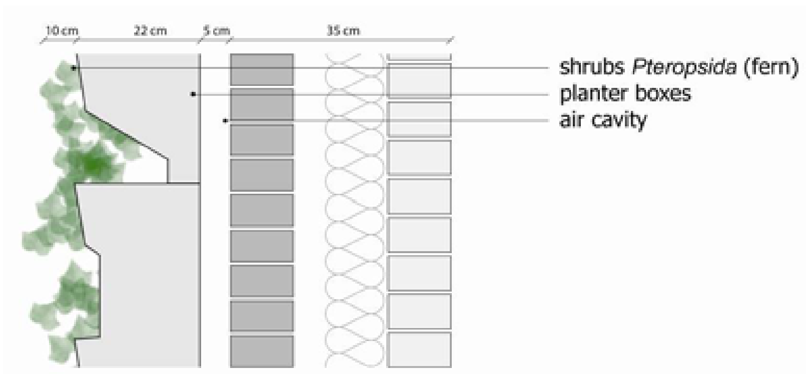


Figure 6.2.4 LWS based on planter boxes with materials layers.

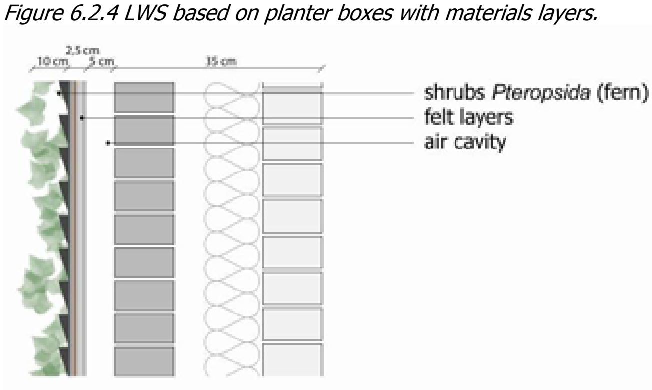


Figure 6.2.5 LWS based on felt layers with materials layers.

As shown in figure 6.2.1, the conventional bare wall (option 1), used as well as basis for the greening systems analyzed, is constructed by masonry, air cavity, insulation material and lime stone. The direct façade greening (option 2) consists in a well grown evergreen climber *Hedera helix*, attached directly to the building surface and planted at the base of the greened façade. The thickness of the *Hedera* foliage is +/- 20 cm. The third system analyzed in this study is an indirect façade greenery (option 3). This system is constituted by steel frames as support for evergreen climbing plants (*Hedera helix* +/- 10 cm). The fourth investigated greened façade, a living wall system (option 4), is based on plastic modules (HDPE), filled with soil and planted with evergreen species (*Pteropsida*), working with a system for water and nutrients. The fifth system (option 5) is a LWS system based on several felt layers as substrate supported by a PVC sheet and planted as well with ferns (*Pteropsida*) and working with a system for water and nutrients. A number of factors are considered in the analysis: raw material depletion, fabrication, transportation, installation, operation, maintenance and waste for the façade(s) area. The transportation distances used are all to and from the city of Delft (The Netherlands).

In order to work with the LCA model, a functional unit should be defined to serve as a basis for comparison of the greening alternatives. According to the ISO 14044 standard, the functional unit is defined as the reference unit through which a system performance is quantified in a LCA. The chosen functional unit in this research is 1 m^2. As basis for calculating the materials and products involved in every system a fictitious façade of 100 m^2 is used.

The results of the analysis are expressed 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. Finally, the assumptions and limitations of analysis and the data will be discussed.

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:

- abiotic depletion (kg Sb equivalents)
- global warming (kgCO_2 equivalents)
- ozone layer depletion (kgCFC-11 equivalents)
- human toxicity (kg1.4-DB equivalents)
- fresh water aquatic ecotoxicity (kg1.4-DB equivalents)
- marine water aquatic ecotoxicity (kg1.4-DB equivalents)
- terrestrial ecotoxicity (kg1.4-DB equivalents)
- photochemical oxidation (kg C_2H_4)
- acidification (kg SO_2 equivalents)
- eutrophication (kg PO_4 equivalents)

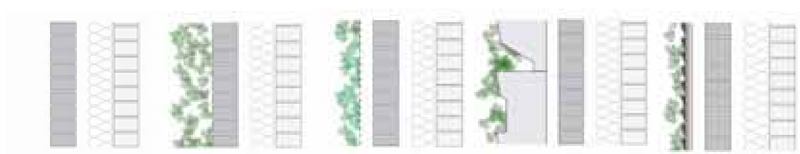
The category marine water aquatic ecotoxicity will not be taken into account because of considerable problems associated with the calculation of the impact in the method. These problems are related to the time a substance is present in the marine ecosystem and missing data for normalization (Blom et 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.

Data inventory

For this life cycle analysis only the components of the building façade directly related to the systems analyzed will be examined. The bare wall is taken as basis for each material inventory; in general a façade is a barrier against environmental conditions to separate the building interior and exterior, nowadays a greening system is added as an extra layer with the previous described multi-functionalities. The difference between the material quantities between the bare façade and the greened ones are the layers involved depending on the greening type: for the direct climber system the layer consists of a single plant layer; the indirect climber system involves also a stainless steel support for the plant; the layer added for the first LWS is based on planter boxes filled with potting soil; the second LWS involves several layers for rooting, waterproofing and supporting.
The materials used for this inventory were obtained from product forms and informations provided by companies (table 6.2.1).

Table 6.2.1 Components and materials for bare wall and green system analyzed.

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



Transportation

The transportation distances used are all to and from the city of Delft (The Netherlands). For the conventional bare wall the majority of the materials are local. All the plants used for the inventory come from a cultivation area 30 km away from Delft. The steel components analyzed for the indirect greening system are manufactured in Rotterdam (18 km from Delft). The distance between Delft and the company of the LWS based on planter box is 15 km and for the LWS based on felt layers the distance is 65 km (tables 6.2.2a-b-c-d-e).

Assumptions

The analysis period to study the environmental aspects and potential impacts is based on a façade's service life of 50 years. 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 plants for living wall systems are simplified as 10 years (10% replacement/year) for the one based on planter boxes and 3.5 years (30% replacement/year) for the felt layers based system.

The life expectancy for the plastic (HDPE) planter boxes is estimated more than 50 years. With reference to a study performed by Riedmiller and Schneider (1992), it is clearly indicated that the service life of PVC layers (structural support for the felt layers) is only 10 years, beside that the whole module (inclusive felt layers) have the same life expectancy. Therefore the whole module is assumed with a life expectancy of 10 years as well.

The automated watering system needed for the LWS concepts (planter boxes and felt layers) 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 computer and sensors (due to the complexity of these systems), therefore it is not included in this analysis. Living wall concepts need, besides the watering system, a nutrient solution which is not taken into account, due to the small (1%) influence. The water consumption for the living wall system based on planter boxes is assumed as a quantity of 1 liter/day (average value for whole year), for the living wall system based on felt layers 3 liter/day (average value for whole year). Watering system are not taken into account for the direct and indirect greening system due to the fact that the climbing plants are rooted into the ground (tables 6.2.2a-b-c-d-e).

For all the greening systems analyzed in this study 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 6.2.2a. 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 6.2.2b. Direct façade greening system material weight (kg), transportation (km) and service life (y) of components.

2.Direct green

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
vegetation	*Hedera helix*	5,5	30	50

Table 6.2.2c. Indirect façade greening system, material weight (kg), transportation (km) and service life (y) of components.

3.Indirect green

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
air cavity	cavity	---	---	---
bolts	stainless steel	0,015	18	---
spacer brackets	stainless steel	0,045	18	---
structural support member	stainless steel mesh	1,55	18	---
vegetation	*Hedera helix*	2,7	30	50

Table 6.2.2d. LWS based on planter boxes material weight (kg), transportation (km) and service life (y) of components.

4.LWS planter boxes

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	0,27	15	---
spacer brackets	steel S235	0,315	15	---
air cavity	cavity	---		---
supporting U section	steel S235	4,62	15	---
planter boxes	HDPE	13,2	15	50
growing material	potting soil	75,6	30	50
vegetation	*Pteropsida*	8	30	10
watering system	PE	0,26	35	7,5
Water demand	tap water	365	0	1

Table 6.2.2e. LWS based on felt layers material weight (kg), transportation (km) and service life (y) of components.

5.LWS felt layers

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	65	---
spacer brackets	steel S235	0,19	65	---
air cavity	cavity	---	---	---
supporting U section	steel S235	4,62	65	---
foam plate	PVC	7	65	10
white fleece	Polypropylene	0,3	65	10
wool fleece	Polyamide	0,6	65	10
PE fleece	Polyethylene (LDPE)	0,045	65	10
black fleece	Polypropylene	0,27	65	10
vegetation	*Pteropsida*	7,5	30	3,5
watering system	PE	0,09	35	7,5
Water demand	tap water	1095	0	1

Interpretation and analysis of LCA results

Environmental burden analysis

A LCA was calculated for the entire life cycle for each component of green façade alternatives. The results show that there is a substantial difference between the greening systems and the bare wall, except for the direct greening system. This is mainly caused by the materials involved for the supporting systems.

Starting from the full environmental profile, only 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.

From figure 6.2.6, it is possible to 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 indirect system and both living wall systems have a high impact compared to the bare wall and the direct greening system. The same trend is noticeable for the fresh water aquatic ecotoxicity, except for the LWS based on felt layers which is more than five times of the indirect and LWS based on planter boxes.

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.

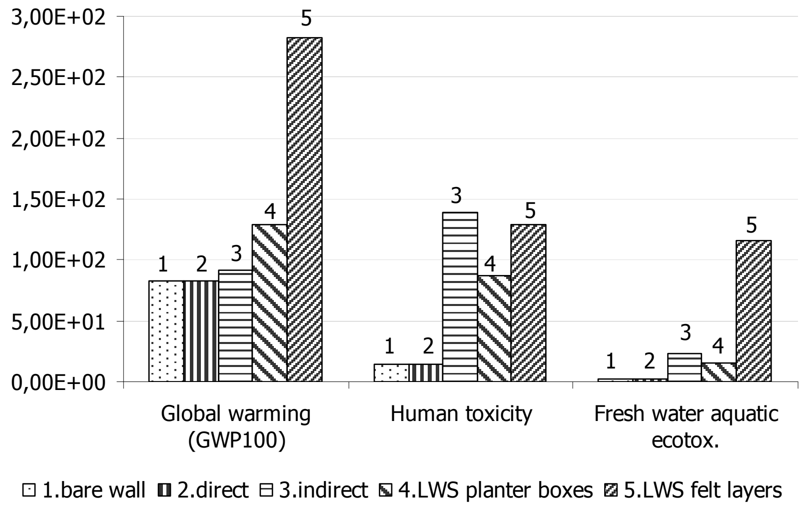


Figure 6.2.6 Environmental burden profile given for global warming, human toxicity and fresh water aquatic ecotoxicity.

The figures 6.2.7a-b-c-d built up for each 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. Due to this the direct greening system has the lowest environmental burden. For this system as for the indirect one, also the vegetation has a very small impact, since it is only related with transportation (no watering and nutrients system and replacement of plants is needed). For the living wall system based on felt layers the waste class has a major impact due to the impossibility of recycling the entire module involved.

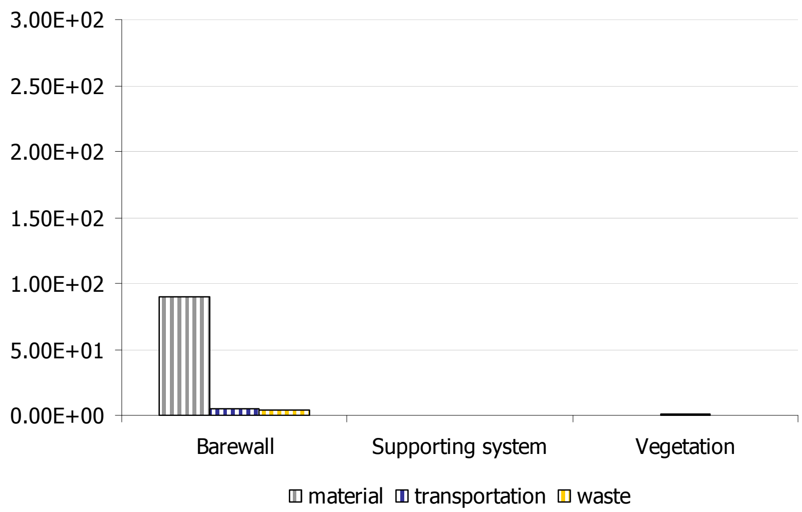


Figure 6.2.7a. Total environmental burden profile for classes material, transportation and waste for direct greening system.

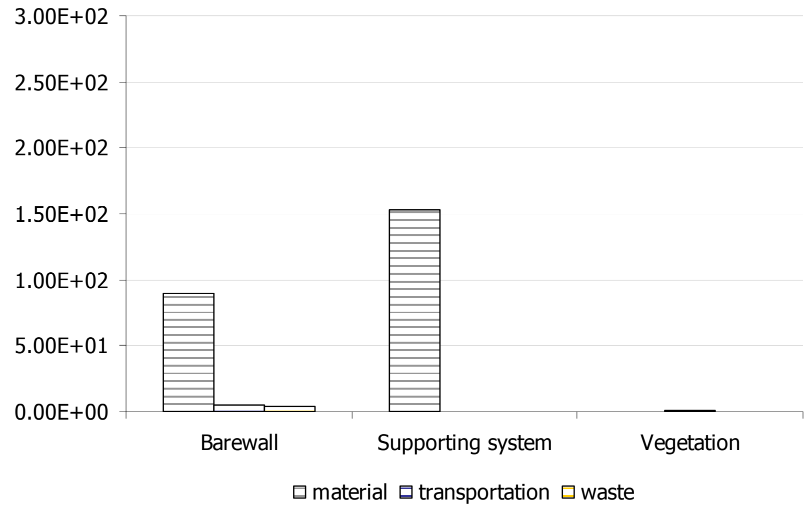


Figure 6.2.7b. Total environmental burden profile for classes material, transportation and waste for indirect greening system.

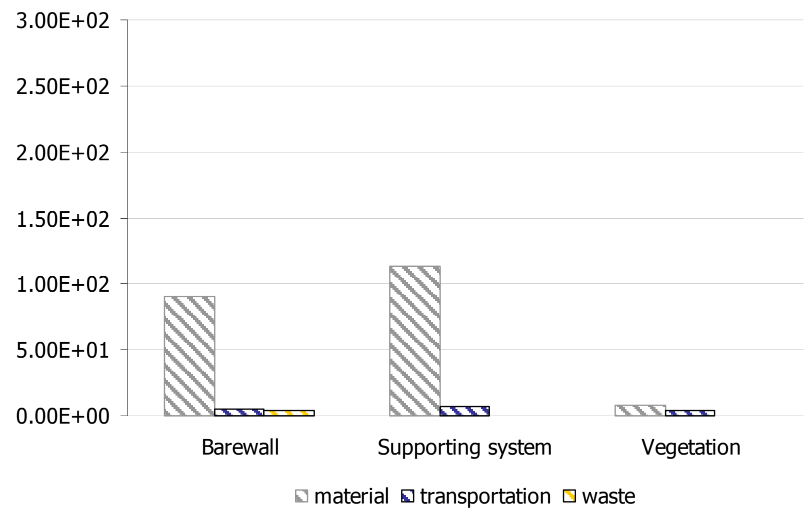


Figure 6.2.7c. Total environmental burden profile for classes material, transportation and waste for LWS based on planter boxes.

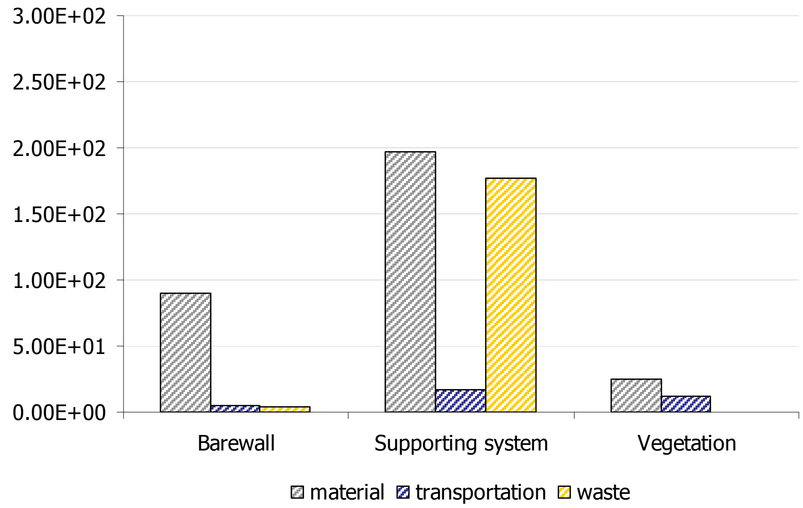


Figure 6.2.7d. Total environmental burden profile for classes' material, transportation and waste for LWS based on felt layers.

Designing green façades for sustainability

This study regards the analysis of four types of greening systems (direct, indirect, LWS based on planter boxes and LWS based on felt layers) and presents an overview of the tendency with respect to the green façades technologies. Since the development in this field is growing rapidly especially the last three to four years, many systems with different materials and characteristics are available. The different systems and materials can have an influence on the environmental burden either positively and negatively. For example for the indirect greening system, based on stainless steel mesh acting as support for climbing plants, other materials, as different types of wood, plastic, aluminum and steel, can be used. Each of the materials enumerated changes the aesthetical and functional properties due to the different weight, profile thickness, durability and cost. Figure 6.2.8 shows (for the indirect greening system) the influence on the environmental burden profile of four different materials that can be used as supporting system. The stainless steel support (as used for this LCA) is roughly 10 times higher than supporting systems based on recycled plastic (HDPE), hard wood (FSC certificated) and coated steel.

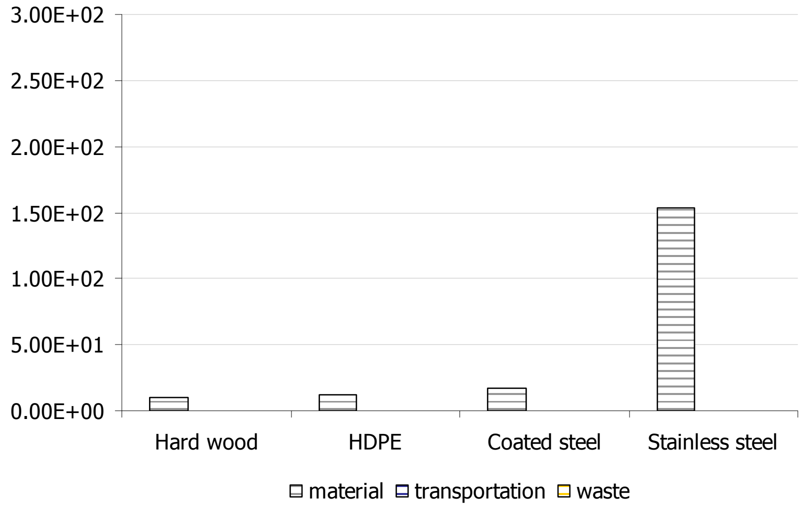


Figure 6.2.8 Environmental burden profile for different supporting materials for indirect greening system.

In the case of living wall systems a sustainable approach can involve, behind the material choice, a higher integration within the building envelope by combining functionalities. In the case of the bare wall analyzed in this study, it is possible for example to skip the outer masonry (figure 6.2.9), since the protection against the environmental parameter can be absolved by a living wall system. Figure 6.2.10 shows the possible reduction of the environmental burden thanks this integration.

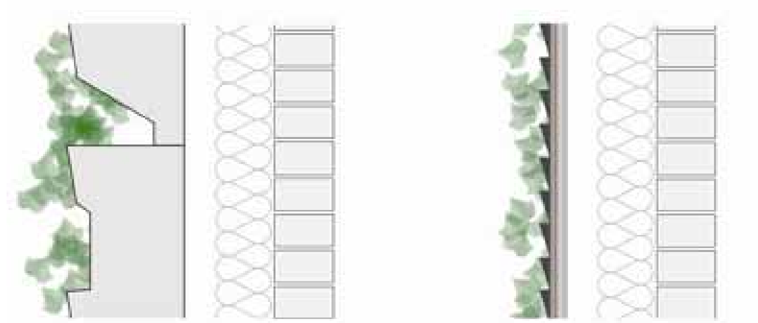


Figure 6.2.9 Living wall systems (based on planter boxes and based on felt layers) without the exterior masonry.

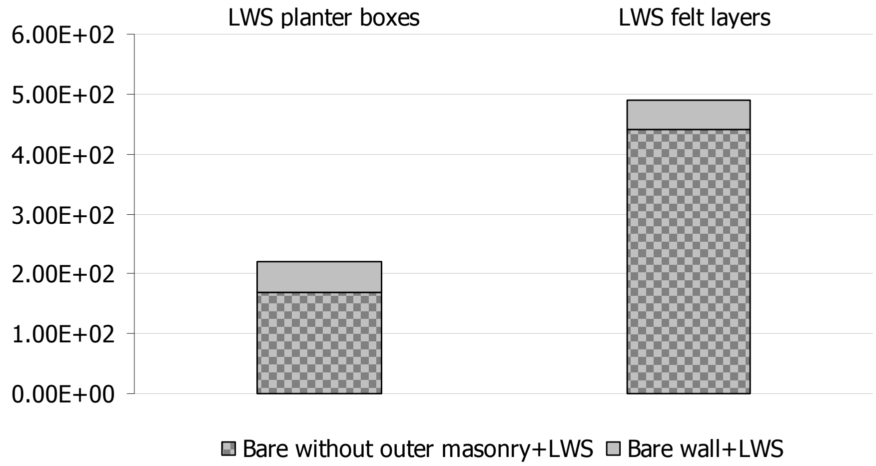


Figure 6.2.10 Comparison between the environmental profiles for two different types of living wall concepts applied to a traditional bare wall and with the omission of the external masonry layer.

Discussion and analysis

Environmental burden

All the systems studied reveal similar dominating impact categories, though the magnitude of this differs considerably. This difference is mainly caused by the supporting material and the replacement both for plants and material. Due to this the living wall system based on felt layers has the largest impact for the global warming and fresh water aquatic ecotoxicity, since it is necessary to replace the panels five times in a service life of 50 years. The human toxicity profile shows a higher impact for the three green façade types with supporting system for plants (indirect, LWS based on planter boxes and LWS based on felt layers). For the systems studied, vegetation contributes to the environmental burden only because of the transport (which is depending on the different replacement required for every system).

The indirect greening system has a high impact profile for the supporting system due to the use of stainless steel. Since stainless steel is a high quality material it could be possible to use it for a life span longer than 50 years. In this case, due to the foliage package that is weaving through the stainless steel mesh, it is not recommended to reuse the material after the service life. Therefore in this case also other supporting materials could be used (hard wood, HDPE, coated steel). As shown in figure 6.2.8, the choice of one of those materials for the supporting system can reduce the environmental burden profile.

The highest environmental burden that is found in the study regards the living wall system based on felt layers; since it is difficult to recycle the panel, the environmental burden of waste has a similar impact profile as the one for the realization. The environmental profile of the living wall systems analyzed can be decreased by higher integration of the building envelope (omitting the exterior masonry).

Benefits of vertical green related to the calculation method

The benefits that can be derived from the green layer are dependant on the growing rate of the plants (covering of the façade). For the direct and indirect system the full covering of the façade by *Hedera helix* is estimated after 20 years (according to Bellomo (2003) 0.5 m/year of vertical growing). For both living wall systems, due to the amount of plants and the several material layers involved, it is possible to calculate the benefits after installation of prefab modules.

For calculating the energy savings for heating, due to the increase of the insulating properties with greening systems, the additional thermal resistance is assumed to be 0.09 Km^2W^{-1}. This assumption is used for all of the direct and indirect greening systems analyzed due to the fact that there is a stagnant air layer in and behind the foliage (Perini et al., 2011). For the living wall systems the thermal transmittance of the substrate and the materials used are added.

For the benefits related to energy savings (increase of *R-value*) in this study a simulation model (*Termo 8.0 Microsoftware*) is used to calculate the influence on the environmental profile for two different types of climates, namely temperate climate (The Netherlands) and Mediterranean climate (Italy), since a green layer affects more the insulation properties for the temperate climate and the cooling potential for the Mediterranean climate.

The simulated buildings used for both locations have a ground floor area of 75 m^2, with a volume of 296 m^3 (three floors) freestanding and situated in an urban context. The whole building envelope is 100 m^2 (fictitious façade used for the basis LCA calculations and includes north, south, west and east orientation) and consists of the same materials and layers analyzed in the LCA (European brick wall, direct greening system, indirect greening system, LWS based on planter boxes, LWS based on felt layers).

The energy savings due to the cooling potential of the four greening systems is based on the research conducted by Alexandri and Jones (2008), regarding the temperature decrease in an urban canyon with green façades and the percentage of reduction that is reached for the air-conditioning (table 6.2.3). For the temperate climate the energy saving for air conditioning in not taken into account, for the Mediterranean climate the calculation is based on the consumption of energy for air conditioning (energy class B) in the northern part of Italy (Genoa). Energy savings from the additional insulation provided by the green façade types and for the cooling potential is found for the building and converted into unit savings to be applied across the LCA calculation.

The calculations described are used to quantifying the indoor effects only, since a lack of data at the moment restricts to evaluate the macro scale environmental benefits.

Also the use of biomass produced (capturing of CO_2) by pruning the *Hedera helix* and by the replacement of plants (*Pteropsida*) from the living wall systems can be converted in energy (kWh). The calculation of this benefit shows a very small impact on the total environmental benefits.

Environmental benefits

The calculation of the savings for the environmental impact as above described is based on the benefits thanks to the energy saving for heating (insulation) and cooling (only for Mediterranean climate). The energy saving thanks to the thermal properties of the systems is calculated through subtraction of the amount of energy that can be saved due to the "extra" insulation layer. For the direct and indirect greening systems the energy saving for heating is estimated as 1.2% of the annual consumption. For the living wall systems based on planter boxes and felt layers the saving was respectively 6.3% and 4%. The temperature decrease thanks to a green layer is estimated to be 4,5 °C (43% energy saving for air conditioning) for the Mediterranean climate and 2,6 for the temperate climate according to Alexandri and Jones (2008).

Table 6.2.3. Energy saving (calculated with Termo 8.0) for heating, energy saving for cooling and temperature decrease for Mediterranean and temperate climate based on Alexandri and Jones (2008).

Greening system	Benefit	Mediterranean climate	Temperate climate
2.Direct green	energy saving for heating	1,2%	1,2%
	temperature decrease	4,5°C	2,6°C
	energy saving for cooling	43%	---
3.Indirect green	energy saving for heating	1,2%	1,2%
	temperature decrease	4,5°C	2,6°C
	energy saving for cooling	43%	---
4.LWS planter boxes	energy saving for heating	6,3%	6,3%
	temperature decrease	4,5°C	2,6°C
	energy saving for cooling	43%	---
5.LWS felt layers	energy saving for heating	4%	4%
	temperature decrease	4,5°C	2,6°C
	energy saving for cooling	43%	---

The categories considered for the environmental benefits thanks to energy saving for heating and air conditioning are, as for the environmental burden, global warming, human toxicity and fresh water aquatic ecotoxicity. From figures 6.2.11a-b (environmental benefits profile for Mediterranean and temperate climate) 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. This is mainly caused by the contribution for the insulation properties of the materials involved. The figures show a similar benefit profile for both direct and indirect such as for the living wall systems; since for the direct and indirect system only the vegetation layer (*Hedera Helix* for both systems) has an influence on the insulating properties. The profiles for the living wall systems have both major benefits. It is a little bit higher for the one based on planter boxes thanks to resistance of the soil package.

Thanks to the energy saving for air conditioning the environmental benefits profile for Mediterranean climate is almost double than the one for temperate climate. The cooling potential and the extra insulation property due to a green layer have a similar influence on the environmental profile for the living wall systems analyzed.

For the direct and indirect greening systems the energy saving for air conditioning has a higher benefit than the energy saving for heating.

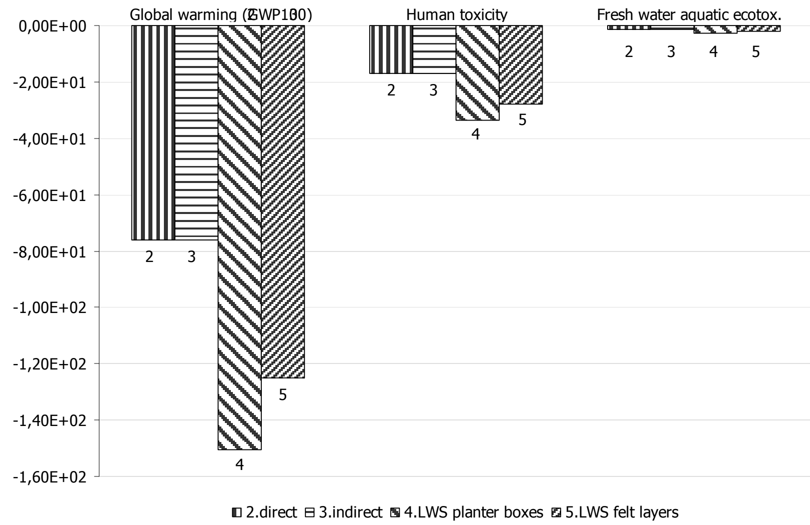


Figure 6.2.11a. Environmental benefits profile (heating and cooling) for Mediterranean climate given for global warming, human toxicity and fresh water aquatic ecotoxicity.

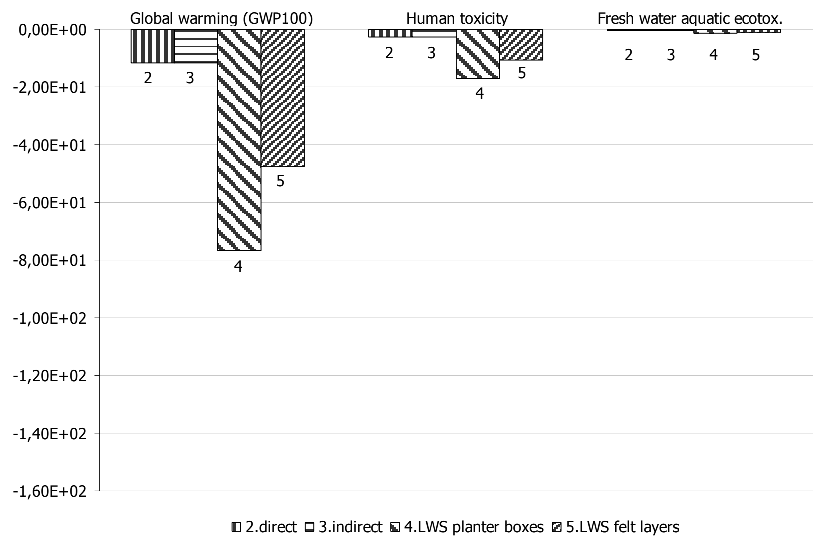


Figure 6.2.11b. Environmental benefits profile (heating) for temperate climate given for global warming, human toxicity and fresh water aquatic ecotoxicity.

Overview

The life cycle analysis presented shows the difference between the greening system analyzed for the environmental burden and for the environmental benefits related to two types of climate (Mediterranean and temperate).

Looking to the environmental burden profiles the indirect greening system and the living wall systems analyzed show a major impact (due to the materials used and the life span) even if, as shown, 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 felt layer appears to be higher even with a different envelope design since the durability aspect plays an important role. For the indirect greening system the outcome can be changed thanks to a different material for the mesh, since the stainless steel has a high contribution on the profile. In general the direct and indirect greening systems have a low 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.
The presented study is depending on The Netherlands to calculate the environmental burden profile with respect to transportation distances. 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). A difference is found in the benefits calculation. For the Mediterranean climate less annual energy consumption for heating is needed, so the energy saving thanks to the greening systems has a lower impact on the positive environmental profile; on the other hand the cooling potential of vegetation plays an important role for the indoor comfort (energy savings for air-conditioning).

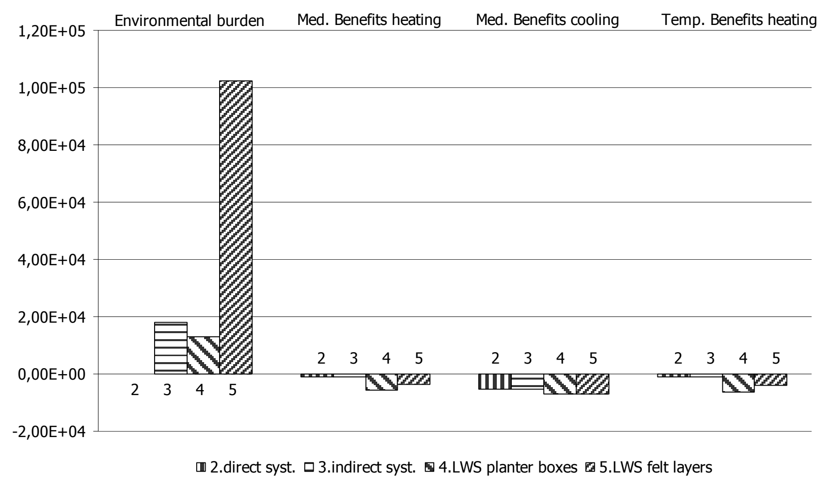


Figure 6.2.12 Environmental burden for the four greening systems (supporting systems + vegetation), benefits for heating and cooling for Mediterranean climate and benefits for heating for temperate climate.

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, considering a system sustainable when the environmental burden is lower than the

environmental benefit profile (figure 6.2.12). 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 is almost sustainable. For the living wall system based on felt layers in both climate types the environmental burden profile is higher than the benefits gained for heating and cooling. The environmental burden and the benefits for heating and cooling are calculated both for the service life of the greening systems studied.
As shown in this article, the choice of a different material (hard wood, HDPE, coated steel), as supporting system for the indirect greening system, can lead to a sustainable option for the Mediterranean climate.

Table 6.2.4 Percentage of reduction given for the environmental burden profile (bare wall + material + vegetation; material + vegetation) with respect to global warming, human toxicity and fresh water aquatic ecotoxicity due to the energy savings for heating and cooling for Mediterranean and temperate climate.

Greening system	Environmental profile	*Tot. burden*	*Green syst. burden*	Benefit heating (Med.)	Benefit cooling (Med.)	Benefit heating (temp.)
1.Bare wall	global warming	*100%*	*0%*	0%	0%	0%
	human toxicity	*100%*	*0%*	0%	0%	0%
	fresh water aquatic ecotox.	*100%*	*0%*	0%	0%	0%
2.Direct green	global warming	*100%*	*0,7%*	12,4%	79,1%	13,9%
	human toxicity	*100%*	*1,3%*	16,2%	103,2%	18,2%
	fresh water aquatic ecotox.	*100%*	*1,6%*	7,0%	44,9%	7,8%
3.Indirect green	global warming	*100%*	*10,2%*	11,2%	71,5%	12,6%
	human toxicity	*100%*	*93,5%*	1,6%	10,6%	1,9%
	fresh water aquatic ecotox.	*100%*	*4,3%*	0,8%	5,0%	0,9%
4.LWS planter boxes	global warming	*100%*	*36,0%*	52,9%	63,7%	59,2%
	human toxicity	*100%*	*84,0%*	17,4%	20,9%	19,5%
	fresh water aquatic ecotox.	*100%*	*83,9%*	7,7%	9,2%	8,6%
5.LWS felt layers	global warming	*100%*	*70,8%*	15,1%	29,1%	16,9%
	human toxicity	*100%*	*88,9%*	7,4%	14,2%	8,2%
	fresh water aquatic ecotox.	*100%*	*97,8%*	0,6%	1,2%	0,7%

In order to carry out this analysis the study relies in part on published data from other green roof and wall researches and practice for estimating these effects. This may introduce some bias, and indicated that this work is subjected to revision as increasing experience with more and better data obtained from green façade researches.

Unquantifiable categories
Other categories may be relevant in green façade applications, but were not included in this analysis either because of a lack of reliable data or incompatibility of the benefit with the tools and categories used in this study. Those categories are mainly related to macro-scale ecological and environmental benefits such as:

- Increased biodiversity.

- Human health.
- Improvement of air quality mainly related to reduction of fine dust levels
- Reduction of the heat island effect with regard the lower amount of heat re-radiated by greened façades and the humidity affected by the evapostranspiration caused by plants.

In this study the micro-scale benefits are only taken into account such as the energy savings for air conditioning and heating. However for quantifying the cooling potential several environmental parameters are involved (humidity, temperature, wind, etc.) and due to a lack of reliable data the calculation is based on an estimation for all the greening systems and it doesn't take into account the specific characteristics per system (living wall systems evaporate a larger amount of water than the systems based on climbers).

Conclusions

The results from the conducted life cycle analysis provide insight in the environmental impact of different greening systems. The energy benefits provided by the greening options make a noteworthy impact in the LCA and are calculated for Mediterranean and temperate climate; for the Mediterranean climate the benefits calculated are roughly two times higher thanks to the energy savings related to the cooling potential. The materials needed to built up the (green) façades are important (environmental impact) when the energy demand of a building can be reduced or when the multifunctionality of the construction due to the integration of vegetation can be increased. From the presented LCA research it can be concluded that:

- The direct greening system has a very small influence on the total environmental burden, for this reason this type of greening, without any additional material involved, is always a sustainable choice for the examined cases.
- The indirect greening system analyzed based on a stainless steel supporting system has an high influence on the total environmental burden; the choice of another material for the supporting system can lead to a sustainable option for the Mediterranean climate (thanks to the energy saving for heating and air conditioning).
- The LWS based on planter boxes has not a major footprint due to the materials involved, since the materials affect positively the thermal resistance of the system. The environmental burden profile could be further improved by a higher integration within the building envelope (combining functionalities).
- The LWS based on felt layers has a high environmental burden due to the durability aspect and the materials used.
- Greening the building envelope considering the materials involved, which, as shown, can have a high influence on the environmental profile, taking into account all the (unquantifiable) benefits it can be a sustainable option.

Despite the need of additional resources initially, the direct greening system, the indirect greening system with a supporting system based on hard wood, coated steel or HDPE and the living wall system based on planter boxes are the environmentally preferable choice when constructing and retrofitting a building, due to the reduction in energy demand for heating and cooling (this study can be easily applied to other construction types). However, it should be noted that this case study is limited to the façade type, climate, and location of the study but is also depending on the assumptions that are made inside the analysis. Further research is essential for improving the analysis to confirm or refute the assumptions made in this study, especially for the unquantifiable categories (increased biodiversity, human health, the improvement of air quality, mitigation of urban heat effect).
Beside this, economical benefits are involved and could be estimated in a life cost analysis thanks to durability, aesthetical value and social factor. Furthermore, lots of systems now available on the market have different characteristics that could influence the environmental profile.

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7 Synthesis and Conclusions

7.1 Introduction

This chapter deals with the general conclusions and recommendations of the doctoral research about different aspects of vertical green. Paragraph 7.2 presents a comprehensive review of the results achieved. This is followed by a number of recommendations (paragraph 7.3) for further research and for the practical implementation of vertical green with respect to sustainability, thermal aspects and design. The final section highlights the general conclusions from the research.

The green building envelope concept involves not only green roofs and green façades but also the total integration of the green building skin on the performance of that building on the climate, indoors as well as outdoors. The presented doctoral research deals only with vertical greened surfaces of buildings and the potential of those greened surfaces on air pollution reduction and the thermal behaviour.

7.2 Achievements of this research

The prime objectives of this research was to gain a better understanding of how vertical green can contribute to air quality improvement and to the thermal behaviour of buildings.

The effectiveness of vegetation as urban particulate sink has focused until now mostly on trees, with leaves considered to effective dust collectors and to improve the urban air quality (Hewitt 2002; Freer-Smith et al., 2005; Maher et al., 2008). The results found, regarding particle adherence on ivy leaves (*Hedera helix*), this doctoral research shows, that *Hedera helix* performs as a sink for fine dust accumulation. However a quantitative relation between dispersed fine particles in the air and the amount of particles accumulated on the leave surface needs further investigation to predict possible decrease of the concentration fine dust levels by vegetation. Using image analyzing software on electron microscope images as developed and shown in the thesis enables to study and examine dust directly on leaves; it is a process that is able to identify particle size and number. The productive approach contrasts with past research methods that identified dust concentration on tree leaves through washing or leaching leaves to determine particle mass (Freer-Smith et al., 2005; Maher et al., 2008) with the different techniques, it is however not possible to compare the particle absorption per mm^2 on ivy with the tree leaves from the past. In addition there is no comparison at the moment with particles suspended in the ambient air, since the current standard is based on particle mass measurements. The missing link in the current method to measure fine dust levels, is that particle mass is not directly related to harmfulness for the human health. From previous research (Pope et al., 2009) it is clear that the amount of inhaled particles (especially the fine and ultra fine particles) is representative for the devastating effect for the human health. From this point of view it is of great importance how vegetation can contribute to particle reduction and which size fractions are accumulated on the leaf surface.

The developed and used electron microscope (ESEM) counting technique in this doctoral research, allows identifying particle composition and size distributions on leaves, without disturbing them by for example washing the leaves. The technique has also shown that fine particles not only adhered on the upper side of leaves, fine particles are also found on the backside of leaves. The backsides of leaves are however not as effective as the upper sides of leaves, but shows the potential of urban greenery (green roofs, greened façades and trees) as a surface related to particle accumulation.
The developed technique is already used by other researchers to study particle accumulation and distribution on leaves. Sternberg et al. (2010) found for example less particle accumulation inside the foliage compared with outer leaves, whereas no differences were found in particle accumulation between the inner and outer leaves sampled from another location, which indicated that more sampling and research is advisable to study this effect (porosity of the foliage, possible stagnant air, moisture content, etc.) in more detail.
The high ratio of surface area (leaves) per square meter façade (leaf area index commonly known as LAI) is often related in literature as the general benefit of vegetation compared to other surfaces related to particle accumulation. It suggest that 1 m^2 of green façade (2.6 up to 7.7 m^2 of leaves for *Hedera helix* according to Bartfelder and Kohler (1987)) can adsorb more particles than 1 m^2 of a traditional façade. However is this hypothesis through?

In paragraph 4.5 different materials have been studied and discussed in relation to fine particle adsorption compared to leaves of *Hedera helix.* The result of this study shows that all of the investigated materials adsorb fine particles however the *Hedera helix* leaves are able to collect more particles per surface area. Beside that the surface area ratio of leaves is much higher than as a traditional façade as earlier mentioned, green façades does not falsify therefore with the idea to lower fine dust levels in dense urban areas.

An important question arises from fine dust particle accumulation of on leaf surfaces: what happens with the accumulated particles once adhered on the leaf surface?

According to literature particles are washed off to the subsoil or can be resuspended into the air again, with all its consequences for the human health. Thönnessen (2002) is the first who shows a *Parthenocissus* leaf (micrograph) that was picked early summer and not fully accumulated with fine particles yet. He also shows a *Parthenocissus* leaf in late autumn where the leaf surface is fully covered with fine particles. Due to the fact that *Parthenocissus* is a deciduous plant species Thönnessen concluded that the accumulated particles together with the leave will fall down to the subsoil where it is taken up by the soil. The theory tells however nothing about the effect of wind or rain on particle loss.
Since *Hedera helix* is an evergreen plant species, it is important to study the potential of resuspension for fine particles once adhered to the leaf surface. Either rain or wind can clean a leaf surface as natural process. In this thesis only the

effect of a heavy rain on the self cleaning effect was investigated with respect to the potential of resuspension of particles into the air again. The developed ESEM micrograph based counting method shows its value compared with previous methods (washing of leaves and measure the mass). The studied *Hedera* leaves were only affected by the simulated rainfall, the developed method to study leaves with image analyzing software, enables to compare micrographs before and after rainfall. Results show that especially the (ultra) fine particles are very strong embedded with the leaf surface; it is not likely that these particles endanger the human health anymore due to resuspension. Since *Hedera helix* is an evergreen plant species one would expect a saturation of the leave surface with fine dust particles. This phenomenon was however not found during the investigation of several leave samples in the presented doctoral research. A possible hypothesis could be that, during the growing season(s), the leave is encapsulated by new leaves and that through the affected air flow by the foliage, less particles can be fixed on inner leave surfaces, secondly the life span of a *Hedera helix* leave is approximately 2 to 3 years before it will die off, wheareas it seems a long period possibly to short to be fully saturated with (ultra) fine particles.
The study is a first step in the comprehensive processes involved between particle adherence and leaf surfaces. Further research about this topic is recommended and important with respect to underlying mechanisms of particle accumulation, effectiveness of different plant species, etc. in order to quantify the relation between vegetation and fine dust levels.

Natural wall vegetation, which can be seen as a concept of vertical green, is an uncontrolled process whereby plants spontaneously grow on building materials. It is a process that typically requires a long-term (more than 30-50 years) growing period. The main characteristics of the latter are that the plants are rooted in or on a building material (mostly stone or rock). Moisture and nutrients are delivered from outside as well as by the building material itself. A new approach of integrating plant growth on building materials is to control the growing process, so that with a relatively short period of time (1 or 2 years) plant growth can occur and that it can be integrated in the designing process. During the doctoral research a first step was done to investigate the possibility for concrete as growing medium for wall vegetation. As shown several plant species survived on the concrete panels, whereas others died during the first half year. It was noticed that the pH of the soil mixture increases over time due to diffusion (pH of concrete ≈13, used soil ≈7) which probably causes dying of some sensitive plant species. It was also observed that a typical wall species as *Cymbalaria muralis* survived and developed well during the observations. It was noticed that without intervention (watering of the plants), the vegetation can hardly survive on the arising arid environment.

Another important aspect of façade greening is related to the thermal comfort and behaviour of buildings. Past research is mainly related to the outside temperature (reduction) conducted by field measurements, as is also carried out in paragraph 5.4 of this doctoral research regarding temperature and wind velocity reduction measurements. The contribution of these measurements (paragraph 5.4) lay

mainly between the different vertical greening systems studied and their characteristics. These characteristics of different greening systems (as vegetation placed directly or indirectly against a façade or the materials and different layers involved regarding the living wall systems) plays a role in the thermal behaviour of a construction as shown in the measurements done in the hotbox (paragraph 5.5). The wind velocity around and within a vertical green system is of interest with respect to the thermal performance of buildings. Currently there are no mechanisms in place to include any calculations into a building's overall thermal performance, which is a lack in the building regulations. Since green façades affect the exterior surface resistance coefficient of buildings by reducing the wind velocity along the façade, the thermal properties of the building improves. Additional in the case of living wall systems an extra air cavity arises between the living wall panels and façade. If this cavity is unventilated or poorly ventilated (staggered air layer), it should be calculated as an extra insulation factor (*R-value*) on top of the thermal resistance of the material layers involved. From the measurements it was found that the wind flow is influenced by a green layer and that it is nearly stagnant air within the air cavity of the living wall system.
The thermal behaviour of a building is not only affected by the wind flow around the building, but also by radiation (sun). A green layer protects the building to adsorb heat into its fabric, besides it can't re-emit adsorbed heat in cooler periods (usually at night) and contributes therefore positively to the urban heat island effect (UHI).

In order to study in detail the effect of a green layer on the temperature gradient through a façade, an experimental set-up was built. The experimental set-up allows measurements with different boundary conditions (temperatures), besides the measurements are reproducible. The bare wall used for this experimental research represents an insulated brick wall normally used for buildings.
The measurements from the designed climate chamber (hotbox) show the effect of different vertical greening systems on the temperature gradient through the greened insulated brick wall. For all the systems studied temperature differences were found between a bare and a greened façade. Nearly no temperature differences were measured for the interior climate after 8 hours of heating, the inhibitory effect of the insulation material used inside the bare wall was clearly noticeable for the direct, indirect and living wall systems. It was also found that the temperature gradient through living wall systems also show an inhibitory effect, which results in significantly lower temperatures (up to 10 °C) of the exterior masonry. Due to these lower temperatures less heat is accumulated in the building envelope, which contributes mostly to the urban heat island effect (outdoor climate). From the results, it can be concluded that there is especially a positive effect of living wall systems on the thermal behaviour of buildings.
It has to be noticed that the interior climate of a building is mostly affected by glazed surfaces (as windows), use, but also by the thermal resistance of the roof and façade itself.

The influence on the interior climate caused by green façades or living walls could be larger for buildings with less thermal mass, like constructions built with timber (wood framing and sheathing) or metal sheets as commonly used for buildings placed on industrial areas. Buildings with less thermal mass are heated up very rapidly under the influence of warm air or the suns radiation, while for heavy buildings (larger thermal mass) more heat can be accumulated before the interior climate is affected.
Living wall systems are of great potential to the thermal resistance of the building due to the characteristics of these systems, like materials used with accompanying thickness, vegetation and the created air cavity.

At the moment there is a small, but growing interest from architects, engineers, companies, institutions and city authorities looking for methods to reduce, either actively or passively, the carbon footprint (and to reduce the total environmental impact) and energy demand of buildings. This movement is quite apart from the current (vertical green) market which is mainly focussed to aesthetics only. The small but growing interest has already led to several research programs such as Rotterdam Climate Initiative, De Groene Buitenspouw and Knooppunt Innovatief Groen, the research programmes are based on cooperation between universities, companies and municipalities.

A remarkable aspect observed during the doctoral research was the thoughtless use in the past of living wall systems regarding the design of new buildings. The integration of both, the façade and living wall system offers the possibility to develop a more sustainable design of a green building envelope. The exterior cladding material, which is normally used for aesthetics and to protect the insulation layer, could be replaced with a living wall system with the same functions (as aesthetics and as a barrier for environmental conditions (sun, frost, rain)). Due to this integration, less building materials are needed (reduction of costs, less environmental impact) and the total construction thickness could be decreased. Besides, the integration of living wall systems will not negatively influence the insulation properties of the façade, since the thermal conductivities of the materials used for these systems are at least equal to the conductivity of the exterior masonry. The integration concept is already positively adopted by several living wall system companies and ready to use into practice.

Greening the building envelope with living wall systems (LWS) considering the materials involved, can have a high negative influence on the environmental burden based on a life cycle analysis (LCA) as shown in paragraph 6.2. However the multi scale benefits of vertical greening are not 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 benefits such as graffiti control, social and economical aspects, ecological functions, noise reduction, etc. regarding greening the building envelope with green façades or living walls, it can be a sustainable option.

7.3 Recommendations for implementation

This section proposes some recommendations for the practical implementation of vertical green as a sustainable façade technology in dense urban areas.

The practical implementation of vertical greenery systems deals with the design of prefab panels (living wall systems) with respect to possible problems with water leakage. Proper detailing is necessary around window and door openings with special profiles to avoid damages and discomfort by the users of the building. To realise a green building envelope with modular greening panels it is advisable (from an aesthetical point of view) to design corner solutions to ensure that these areas can be greened as well, because at the moment aluminium or coated steel plates are used to cover the edges of a greening system.
The integral design of a vertical greening system with the façade to combine functionalities, as discussed in this thesis, needs attention with respect to add water proof membranes (permeable) to ensure that the underlying insulation material absorb moisture resulting in a decrease of thermal resistance of the insulation material. Besides, solutions have to be developed for (cavity) anchors to attach the panels with respect to avoid thermal bridges within the green façade design.

To improve the durability and sustainability aspect of green façade systems a deliberate material choice is necessary. Regarding the durability aspect a guaranteed service life of the materials involved for the living wall systems is advisable to avoid unnecessary intermediate replacements of the panels during the life span of the building. For the direct and indirect green façade systems in practice normally stainless steel supporting systems are used. Due to the properties of the vegetation layer (acting as a raincoat) the choice of stainless steel is maybe luxurious, whereas the choice of other less expensive materials (HDPE, hardwood, steel) can be used with the same function characteristics. From a sustainability point of view choosing for other supporting materials than stainless steel, influences the environmental impact positively. For living wall concepts the integration within the façade for new buildings can save on material costs, construction thickness and on the environmental impact. It is therefore advisable to apply this concept for the designing process of green façades for new buildings.
The functionality of green façades can be extended by using rainwater collected on the roof for the hydroponic system. Rainwater storage for example in the basement of the building should be implemented if possible, to reduce the amount of drinking water used for watering and to contribute to delayed rainwater drainage to the sewer.

For a wide application of vertical greening systems (to ensure affordability for the building owner) the comparative market need to establish lower prices, especially regarding the living wall systems. In addition subsidy from the government or municipalities should meet similar as for green roofs at the moment to ensure that more vegetation will be applied in dense urban areas with a lack of space for urban green. At the moment there are already a few municipalities (Rotterdam, Amsterdam, Utrecht and Eindhoven) in the Netherlands who give subsidy to construct and stimulate vertical greened façades.

In all, with all the encouraging results of vertical greening systems, it is with anticipation that vertical greening systems will gradually become one of the driving forces for realizing green building envelopes in dense urban areas world wide.

7.4 Recommendations for further research

This section proposes some recommendations for further research about vertical greening systems and their effect on the environment.
More quantitative research is recommended, most of these aspects deal with findings done in this doctoral research. Results obtained during the particulate matter adsorption, wind measurements, experiments dealing with the thermal behaviour and investigation about the sustainability highlight the promising aspects of vertical greenery systems. For further development of the results, studies should move on and should be analyzed at actual building façades greened with vertical greening systems (especially living wall systems). By doing so, the performance of various thermal parameters may reveal more insight as for the physical structure, materials and dimensions of the panels holding different varieties of artificial substrates, plant species, composition, depth and moisture content of the vertical greenery systems. More future experiments are essential and can be tailored to study the impact of these factors individually as well as to formulate an optimal vertical green configuration for the different vertical greening systems with respect to the thermal behaviour as well as for the reduction of air polluting substances.

The number of particles with accompanying size distribution count on leaf surfaces has to put in relation (quantitatively) with the number of particles (with accompanying size distribution) that are present in the ambient air. The current measurements formulated in the standards are based on particle mass instead of the number particles, which gives no information about the hazardous effect of those particles for the human health.
Regarding the quantification of the reduction of fine dust levels in the air, not only field measurements are recommended, also more measurements under laboratory conditions are necessary. Laboratory experiments provide more certainty about repetition of the fine dust levels than in practice, were particles are formed or broken down under the influence of sun radiation. Field measurements however can be used to validate the experimental findings. In relation to quantify the effect of vertical green on reducing fine dust levels, computational fluid dynamics (CFD) modelling of air and particle flow within vegetation gives more insight to the potential of vertical greenery to adsorb fine dust particles with respect to optimal configuration of the greening system.

The thermal behaviour of vertical greening systems as tested in this doctoral thesis (measurements in the climate chamber) requires further investigation regarding the summer measurements. It is recommended to measure the vertical greening systems longer than 8 hours to ensure steady state situations as necessary for the calculation method. Further research about the evaporative character of the greening systems in a closed box needs to be studied to understand the effect on the thermal properties better, it will probably leads to other dimensions of the used experimental set-up (hotbox).

Extensive measurements regarding the sound adsorption properties of vertical greening systems have to be conducted to understand the effect of greening façades in an urban context better. Living wall systems tend to be more successful due to the materials used for realizing plant growth, such as substrates or soft felt layers with a high potential of adsorption.
The appliance of living wall concepts, which are a relative new concept of façade greening, need more investigation to possible damage mechanisms. Deterioration of growing media such as substrates or felt layers are key elements inside the uncertainty for durability in façade design. In relation additional research about the blocking/filtering of solar radiation (UV-light) by the foliage must give more insight in positive extension of material degradation. To develop artificial plant growth on building materials, as for example shown in this thesis for concrete, more research is necessary to realise this form of greening structures. Frost experiments can be used to predict durability problems with respect to decay of the concrete. The moisture balance and the pH of concrete needs to be investigated more deeply to succeed with plant growth on the building material itself.

7.5 Conclusions

This chapter comprises of the main outcomes from the executed research. The prime objective was to investigate the possibilities for greening the building envelope. The conclusions from the thesis are as follows:

- Vegetation performs as a sink for particulate matter, especially for the finer fractions (smaller than $PM_{2.5}$).
- The wind velocity around the building envelope is affected due to the vegetation layer; it is promising especially for living wall concepts were a stagnant air layer is created between façade and the LWS panels.
- An integrated approach in façade design for living wall systems (LWS) is a justified building method with respect to the thermal properties and sustainable building methodology.
- Green façade systems contribute substantially to mitigation of the urban heat island (UHI) effect through less accumulation of heat by the building envelope.
- Insulation material is irreplaceable by vertical greening systems, either it is beneficial for the thermal behaviour indoor as well as outdoors.
- The developed ESEM counting method seems to be a proper way to classify fine dust accumulation on leaf surfaces.

- Vertical greening systems affect the thermal behaviour of buildings more with less thermal mass.
- Not only the upper part of leaves adsorb fine particles also the backside is capable for collecting particles.
- Due to the foliage with a high surface ratio, a modified micro climate is created which acts more beneficial for fine dust accumulation than traditional cladding materials for façades.
- The designed climate chamber to test 1 m^2 of a greened façade could be improved to increase the volume of the exterior chamber. The relative humidity should be limited due to this increase to outdoor environmental conditions.

Green façades and living walls can improve the environment in cities. They offer more surfaces with vegetation and, at the same time, contribute to several positive aspects like air pollution reduction, increased biodiversity, mitigation of urban heat, sound adsorption and to the improvement of the thermal performance of buildings. As shown vegetation performs as a sink for (ultra) fine particles and the presence of a vegetation layer contributes to the thermal resistance of the building. Calculations show that the choice of a greened façade does not greatly influence the thermal resistance of a thermally well insulated façade but has to be taken into consideration when the façade is not fully thermally insulated (retrofit). Regarding the urban heat island effect, less heat accumulation occurs in the case of a green building envelope, it is therefore a wise choice to apply greened surfaces especially in warmer climates.

Finally, although the contribution of green façades and living walls may be small at the building scale, they are, however energy efficient and ecologically relevant, and are recommended whenever practicable.

References related to the thesis

- **Abu Sa'deh, A.J., Luscuere, P.G., 2000.** Ecological assessment of building designs existing methodologies and tools. Congrès Integrated life-cycle design of materials and structures ILCDES 2000 RILEM / CIB / ISO international symposium, Helsinki, vol. 14, pp. 355-359.
- **Akabari, H., Pomerantz, M., Taha, H., 2001.** Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. Solar energy vol. 70, no 3, pp. 295-310, 2001.
- **Anonymus, 2005.** Green roofs, ecological design and construction. Earth pledge, *Schiffer Books.*
- **Anonymus, 2007.** Toepassingen van groene daken in Rotterdam. Uitgave Gemeente Rotterdam.
- **Baas, R., Warmenhoven, M., 2003.** Praktijkonderzoek Plant & Omgeving (PPO), Planttemperatuur in relatie tot omgevingsfactoren: metingen voor mogelijke toepassing in klimaatregeling.
- **Bartfelder, F., Köhler, M., 1987.** Experimentelle untersuchungen zur function von fassadenbegrünungen, Berlin.
- **Bartfelder, F., Köhler, M., 1987.** Experimentelle untersuchungen zur function von fassadenbegrünungen, Abbildungen, tabellen und literaturverzeichnis, Berlin.
- **Bass, B., Martens, R., Alcazar, S.S., 2008.** Roof-envelope ratio impact on green roof energy performance. Urban ecosyst (2008) 11:399-408 DOI 10.1007/s11252-008-0053-z.
- **Beckett, K.P., 1989.** Arboriculture: Particle pollution removal by urban trees. *University of Sussex at Brighton.*
- **Beckett, K.P., Freer-Smith, P.H., Taylor, G., 2004.** Deposition velocities to Sorbus aria, Acer campetre, Populus deltoides x trichocarpa `Beaupre, Pinus nigra and x Cupressocyparis leylandii for coarse, fine and ultra-fine particles in the urban environment. Environmental Pollution, 133(1), 157-167.
- **Becquerel, A.C., 1847.** *Eléments de physique terrestre et de météorologie*
- **Becquerel, A.C., 1875.** *Des forces physico-chimiques et de leur intervention dans la production des phénomènes naturels* .
- **Beeldens, A., 2008.** Fotokatalyse: Een toekomsttechniek? Onderzoekscentrum voor de Wegenbouw (OWC).
- **Bellomo A., 2003.** Pareti verdi, Sistemi editoriali, Napoli, Italy.
- **Bezemer, V., Visschedijk, P.A.M., 2003.** Groene meters deel II. Analyse van het stedelijk groen in de G30 steden. Alterra-rapport 833, Wageningen.
- **Bohemen, van, H.D., 2005.** Ecological engineering, bridging between ecology and Civil engineering, Aeneas technical publishers.
- **Bouwbesluit 2003.** Dutch building regulation 2003.
- **BioScience, 2007.** http://www.bioone.org/loi/bisi.
- **Blanc. P., 2009.** La façade végétale et l'intégration d'éléments naturels, Architecturaal symposium "De levende gevel", KHBO-Brugge (2009)
- **Bloemen, H.J., van Bree, L., 1998.** Fijn stof in Nederland- Een tussenbalans, Bilthoven: Rijksinstituut voor volksgezondheid en milieuhygiene RIVM rapportnr 650010006.
- **Blom, I., Itard, L., Meijer, A., 2010.** LCA-based environmental assessment of the use and maintenance of heating and ventilation systems in Dutch dwellings, Building and environment 45 (2010) 2362-2372.
- **Brenneisen, S., 2003.** The benefits of biodiversity from green roofs: key design consequences.
- **Bruse, M., Thönnessen, M. and Radtke, U., 1999**. Practical and theoretical investigation of the influence of facade greening on the distribution of heavy metals in urban streets. *Proceedings International Conference on Urban Climatology & International congress of Biometeorology, Sydney*, 8-12 (1999).
- **Bussotti, F., Grossoni, P., Batistoni, P., Ferretti, M., Cenni, E., 1995.** Preliminary studies on the ability of plant barriers to capture lead and cadmium of vehicular origin. Aerobiologia 11 (1995) 11-18.

- **Carter, T., Keeler, A., 2008.** Life cycle cost benefit analysis of extensive vegetated roof systems. Journal of environmental management 87 (2008) 350-363.
- **Chow, J.C., Watson, J.G. and Lowenthal, D. H., 1996.** Sources and chemistry of PM10 aerosol in Santa Barbara County, CA. Atmospheric Environment 30(9), 1489-1499.
- **Corrado M., 2010.** Il verde verticale, Sistemi Editoriali, Napoli, Italy
- **Currie, B., A., Bass, B., 2008.** Estimates of air pollution mitigation with green plants and green roofs using the UFORE model. Urban Ecosyst (2008) 11:409-422 DOI 10.1007/s11252-008-0054-y.
- **Darlington. A., 1981.** Ecology of wall, Heinemann education books.
- **Doernach, R., 1979.** Uber den Nutzungen von Biotektonischen Grunsystemen. Garten und Landschaft 89 (6).
- **Donnelly, M.C., 1992.** Architecture in the Scandinavian countries. Massachusetts institute of technology.
- **Dunnet N., Kingsbury N., 2004.** Planting Green Roofs and Living Walls, Timber Press, Oregon.
- **Ensikat, H.J., Boese, M. Mader, W., Barthlott, W. and Koch, K., 2006.** Crystallinity of plant epicuticular waxes: electron and X-ray diffraction studies. *Chemistry and Physics of Lipids*, 144 - 1, 45-59 (2006).
- **Eumorfopoulou, E.A., Kontoleon, K.J., 2009.** Experimental approach to the contribution of plant covered walls to the thermal behaviour of building envelopes. Building and Environment 44 (2009) 1024-1038.
- **Eumorfopoulou, E.A., Aravantinos, D., 1998.** The contribution of a planted roof to the thermal protection of buildings in Greece, Energy and Buildings 27 (1) (1998), pp. 29–36.
- **Feng, C., Meng, Q., Zhang, Y., 2010.** Theoretical and experimental analysis of the energy balance of extensive green roofs. Energy and Buildings 42 (2010) 959-965.
- **Fjeld, T., Veiersted, B., Sandvik, L. ,Riise, G., Levy, F., 1998.** "The Effect of Indoor Foliage Plants on Health and Discomfort Symptoms among Office Workers." Indoor Built Environ, 1998, 7; p204-209 ed.
- **Fowler, D., Cape, J.N., Unsworth, M.H., 1989.** Deposition of atmospheric pollutants on forests. Philosophical Transactions of the Royal Society of London 324, 247-265.
- **Fowler, D., 2002.** Pollutant deposition and uptake by vegetation. In Bell, J.N.B., Treshow, M., Air Pollution and Plant Life, Second Edition, p.43.
- **Fowler, D., 2001.** Coyle, M., AsSimon, H.M., Ashmore, M.R., Bareham, S.A., Battarbee, R.W., Derwent, R.G.,Erisman, J.W., Goodwin, J., Grennfelt, P., Hornung, M., Irwin, J., Jenkins, A., Metcalfe, S.E., Ormerod, S.J., Reynolds, B., Woodin, S., Hall, J., Tipping, E., Sutton, M., Dragosits, U., Evans, C., Foot, J., Harriman, R.,Monteith, D., Broadmeadow, M., Langan, S., Helliwell, R., Whyatt, D., Lee, D.S., Curtis, C., 2001 National Expert Group on Transboundary Air Pollution, 2001. Transboundary air pollution: acidification, eutrophication and ground-level ozone in the UK, *NEGTAP 2001*.
- **Getter, K.L., Rowe, B.D., 2006.** The Role of extensive green roofs in suistainable development. Hortscience 41(5):1276-1285.
- **Gilbert, O.L., 1991.** The Ecology of Urban Habitats. Chapman & Hall, London, UK.
- **Gomez, F., Gaja, E., Reig, A., 1997.** Vegetation and climatic changes in a city, Ecological Engineering 10 (1998) 355-360.
- **Heidt, V., Neef, M., 2008.** Benefits of Urban Green Space for Improving Urban Climate. Ecology, Planning, and Management of Urban Forests 2008, Part I, 84-96, DOI: 10.1007/978-0-387-71425-7_6.
- **Hendriks, N., 2008.** Gevels in't groen; aanwijzingen voor het ontwerpen van groene gevels. SBR, Rotterdam.
- **Hendriks, N., Koers, G., 2009.** Gevelreeks NBD-BDA deel 8: Groene gevels, Den Haag.
- **Hendriks, C. F.,** Bijen, J.MJ.M, Felix, F., Fraaij, A.L.A., Janse, H., de Munck, E.D., Reintjes, R.C., Schutte-Postma, E.T., Stroeven, P., Vogtlander, J.G., van der Wegen, G.J.L., 2000. Durable and sustainable construction materials. ISBN 90-75-365-30-6.
- **Hermy M., Schauvliege M. en Tijskens G, 2005.** Groenbeheer, een verhaal met toekomst. *Velt in samenwerking met afdeling Bos & Groen, Berchem*.
- **Hosker, R.P., Lindberg, S.E., 1982.** Review: atmospheric deposition and plant assimilation of gases and particles. Atmospheric Environment 16(5):899-910.

- **Innovatie project luchtkwaliteit (IPL), 2006.** Kennisdocument Vegetatie-luchtkwaliteit ten behoeve van het uitvoeren van een pilotproject langs rijkswegen rapportnummer DWW 2006-094 /IPL 06.00019
- **Innovatie programma luchtkwaliteit (IPL), 2009**. Ministerie van Verkeer en Waterstaat, 2009. Invloed van TiO_2 coatings op de luchtkwaliteit. Eindrapport onderzoek naar de werking van TiO_2 coatings op geluidschermen ter vermindering van NO_2 concentraties in de lucht langs snelwegen. Rapportnummer IPL-4a, 2009.
- **Integrale gewijzigde wet geluidhinder, 2007.** Ministerie van volkshuisvesting, Ruimtelijke ordening en Milieubeheer (VROM).
- **Integrale tekst van het bouwbesluit, 2003.** Ministerie van volkshuisvesting, Ruimtelijke ordening en Milieubeheer (VROM).
- **ISO 14044**: Environmental management – life cycle assessment – requirements and guidelines. International Organization for Standardization; 2006.
- **Johnston, J., Newton, J., 2004.** Building Green: A guide to using plants on roofs, walls and pavements. Published by Greater London Authority City Hall, ISBN 1 85261 637 7.
- **Kaltenbach, F., 2008.** Living walls, Vertical gardens – from the flowerpot to the planted system façade. Detail nr 12 (2008) 1454-1463
- **Köhler, M., 1988**. Besiedlung von Kletterpflanzan durch Insekten und Spinnen in Berlin (West). (Colonisation of Climbing Plants by Insects and Spiders in Berlin). Zeitschrift fur Angewandte Zoologie. (German Journal for Applied Zoology), 75(2), pp. 195-202.
- **Köhler, M., 2006.** Long-Term vegetation research on two extensive green roofs in Berlin. Urban Habitats, volume 4, number 1 ISSN 1541-7115.
- **Köhler, M., 2008.** Green façades - a view back and some visions, Urban Ecosyst 2008 vol. 11, pp. 423-436.
- **Köhler, M., 1993.** Fassaden- und Dachbegrünung. Ulmer Fachbuch Landschafts- und Grunplanung, Stuttgart. ISBN 3-8001-5064-6.
- **Kosareo L., Ries R., 2007.** Comparative environmental life cycle assessment of green roofs, Building and Environment 42, 2606-2613
- **Koch, K., Ensikat, H.J., 2008.** The hydrophobic coatings of plant surfaces: Epicuticular wax crystals and their morphologies, crystallinity and molecular self-assembly. *Micron,* 39 - 7, 759-772 (2008).
- **Krusche, P., Krusche, M., Althaus, D., Gabriel, I., 1982.** Ökologisches bauen. Herausgegeben vom umweltbundesamt, Bauverlag.
- **Liesecke et al., 1985.** Dachbegrunung, Parzer, Berlin.
- **Lundholm, J.T., 2007.** Green roofs and : A habitat template approach, *Urban habitats, vol. 4, number 1, p. 87-102.*
- **Maes, N.C.M., 1992.** Gevelbegroeiing en klimplanten. Rijksdienst voor het cultureel erfgoed, Flora en monumenten. RDMZ RV 1992/28-8 UDC 58:72.025.
- **Mariq, M., 2010.** *Nanoparticles in Medicine and Environment*, Marijnissen, J. & Gràdon, L., 19 – 37 (2010).
- **Matthijsen, J.,Visser, H., 2006.** PM10 in Nederland, rekenmethodiek, concentraties en onzekerheden. Milieu- en natuurplanbureau (MNP) rapport 500093005/2006.
- **McCartney, H.A. et al., 1982.** Electric charge and the deposition of spores of Barley Mildew *Erysiphe Graminis*, *Atmospheric Environment*, 16 - 5, 1133-1143 (1982).
- **Minke, G.,Witter, G., 1982.** Häuser mit grünen pelz. Ein handbuch zur hausbegrünung.
- **Milieu- en Natuurplanbureau (MNP), 2008.** De fijnere fractie van fijn stof ($PM_{2.5}$): normen en haalbaarheid.
- **Mitsch, W.J. and S.E. Jørgensen, 1989.** Ecological Engineering. An introduction of Ecotechnology. John Wiley and Sons. New York.
- **Mitsch, W.J. and S.E. Jørgensen, 2004.** Ecological Engineering and Ecosystem Restoration. John Wiley and Sons. New York.
- **Miyawaki, A., 1998.** Restoration of urban green environments based on the theories of vegetation ecology, Ecological Engineering 11 (1998) 157-165.
- **MNP and RIVM, 2005.** Buijsman, E., Beck, J.P., van Bree, L., Cassee, F.R., Koelemeijer, R.B.A. J., Matthijsen, R., Wieringa, T., Wieringa, K., 2005. Fijn stof nader bekeken. Rapport Milieu- en Natuurplanbureau (MNP) en Rijksinstituut voor Volksgezondheid en Milieu (RIVM). Rapportnummer 500037008, ISBN 90-6960-124-9.

- **Morales, Dominic J., 1989.** "The contribution of trees to residential property value." Journal of Arboriculture (Journal of Arboriculture), 1980: 305.
- **Müller, F., Michel, W., Schlicht, V., Tietze, A. and Winter, P., 2007.** Self-Cleaning surfaces using the Lotus effect. *Handbook for Cleaning/Decontamination of Surfaces*, *791-811* (2007)
- **Natuur balans, 1999.** Rijksinstituut voor volksgezondheid en milieu (RIVM) Onderzoeksrapport 408663001, ISBN: 9014062281.
- **NEGTAP, 2001.** Transboundary air pollution: acidification, eutrophication and ground-level ozone in the UK. Report of the National Expert Group on Transboundary Air Pollution (NEGTAP) for the UK Department for environment, food and rural affairs, Scottish Excecntive, the National Assembly for Wales/Cynulliad Cenedleathol Cymru and the Department of the Environment for Northern Ireland, CEH, Edinburg (2001) 314 pp.
- **Niemietz, A., Wandelt, K., Barthlott, W. and Koch, K., 2009.** Thermal eation of multi-component waxes and thermally activated formation of nanotubules for superhydrophobic surfaces. *Progress in Organic Coatings*, 66 - 3, 221-227 (2009).
- **Nowak, D.J., Mcpherson, E.G., Rowntree, R.A., 1994.** Chicago's Urban Forest Ecosystem: *Results of the Chicago Urban Forest Climate Project, United States Department of Agriculture, General Technical Report* NE-186
- **Odum, H.T., 1995.** Scales of ecological engineering. Ecological Engineering 6 (1996) 7-19
- **Odum, H.T., 1983.** Systems Ecology. Wiley, New York. Reprinted in 1994 by University Press of Colorado, Niwot, CO.
- **Office of the Federal Environmental Executive, 2003.** "The Federal Commitment to Green Building: Experiences and Expectations.
- **Oosterbaan, A, Tonneijck A.E.G, de Vries, E.A., 2006.** Kleine landschapselementen als invangers van fijn stof en ammoniak. Alterra-rapport 1419, Alterra, Wageningen.
- **Osmundson, Th., 1999.** Roof Gardens; history, design and construction. W.W. Norton and Company. New York.London.
- **Owen, P.J., 1994.** Influence of botanic garden experience on human health (Master thesis). Manhattan: Kansas State University, Department of Horticulture, Forestry and Recreation Resources.
- **Pal, A.K., Kumar, V. and Saxena, N.C., 2000.** Noise attenuation by green belts, *Journal of Sound and Vibration*, 234 - 1, 149–165. (2000)
- **Peck, S.W. et al., 1999.** Greenbacks from green roofs: forging a new industry in Canada, Status report on benefits, barriers and opportunities for green roof and vertical garden technology diffusion, environmental adaptation research group, Canada.
- **Pekkanen J, Timonen KL, Tittanen P, Vallius M, Lanki T, Sinkko H., 2000.** Exposure and Risk Assessment for Fine and Ultrafine Particles in Ambient Air. National Public Health Institute.
- **Perini, K., Ottelé, M., Haas, E.M., Fraaij, A.L.A., Raiteri, R., 2011.** Vertical green systems and the effect on air flow and temperature near the façade. Article in press Building and Environment 2011..
- **Peters, B.A., 2011.** Groene gevels – onderzoek naar de bouwfysische eigenschappen van vertical groen, afstudeerrapport. Technische Universiteit Delft, faculteit Bouwkunde 2011.
- **Polinger, K., 1998.** Gardens of Eden: Exotic Flora and Fauna in the Ancient Near East. Transformations of Middle Eastern Natural Environments Legacies and Lessons, Yale University, pp. 320–329.
- **Pope, A. C., Ezzati, M., Dockery, D.W., 2009.** Fine-Particulate Air Pollution and Life Expectancy in the United States. The new England journal of medicine; N Engl J Med 2009; 360:376-86.
- **Powe, N.A., Willis, K.G., 2003.** Mortality and morbidity benefits of air pollution (SO2 and PM10) absorption attributable to woodland in Britain. Journal of Environmental Management 70 (2004) 119-128.
- **Powe, N.A., Willis, K.G., 2004.** Mortality and morbidity benefits of air pollution (SO_2 and PM_{10}) absorption attributable to woodland in Britain, *Journal of Environmental Management* , 70, 119-128 (2004).
- **Rath, J., Kießl, K., 1989.** Auswirkungen von Fassadenbegrünungen auf den Wärme- und Feuchtehaushalt von Aussenwänden ubd schadensrisiko. Fraunhofer-Institut für Bauphysik, IBP-Bericht Ftb-4/1989.

- **Riedmiller, J., Schneider, P., 1992.** Maintenance-free roof gardens: new urban habitats. Naturwissenschaften 1992; 79 (12):560-1.
- **RIVM**; http://www.rivm.nl/milieuportaal/dossier/fijnstof/
- **RIVM, 2010.** Opened in December 2010 from the website of National institute for public health and the environment (RIVM).
- **Robles, M., 2004.** Tuin&landschap (23).
- **Rural area council, 2005.** Recht op groen; Advies over de groene kwaliteit van de openbare ruimte Deel 1 Beleidsadvies, Publicatie RLG 05/6.
- **Rutgers, R., 2011.** Living façades - A study on the sustainable features of vegetated façade cladding, afstudeerrapport. Technische Universiteit Delft, faculteit Bouwkunde 2011.
- **Samuels, L., Kunst, L. and Jetter, R., 2008.** Sealing plant surfaces: cuticular wax formation by epidermal cells. *Ann. Rev. Plant Biol.*, 59, 683-707 (2008).
- **Stec, W.J., Van Paassen, A.H.A. and Maziarz, A., 2005.** Modelling the double skin façade with plants, *Energy and Buildings*, 37, 419-427 (2005).
- **Smith, W. H., Dochinder, L.S., 1976**. Capability of metropolitan trees to reduce atmospheric contaminents. Proc. Better Trees for Metropolitan Landscapes, 4–6 November 1975, Washington, DC, Gen. Tech. Rep. NE-22, U.S. Dep. Agric., For. Serv., NE For. Exp. Stn, Broomall, PA (1976), pp. 49–59.
- **Smith, W. H., 1976.** Removal of atmospheric particulates by urban vegetation: implications for human and vegetative health. The journal of biology and medicine 50 (1977).
- **Steltman, P., 2005.** Fijn stof aanpakken met openbaar groen.
- **Tammes, E., Vos, B.H., 1984.** Warmte en vochttransport in bouwconstructies.
- **Tatano V., 2008.** Verde: naturalizzare in verticale, Maggioli Editore, Santarcangelo di Romagna, Italy.
- **Teeuw, P.G. and G.M. Ravesloot, 1997.** Begroeide daken in Nederland. *Delft University Press*.
- **Thönnessen, M., 2002.** Elementdynamik in fassaden begrünendem wilden Wein, *Kölner Geographischer Arbeiten*, *Heft 78, Köln.*
- **Thönnessen, M., Werner, W., 1996.** Die fassadenbegrünende Dreispitzige Jungfernrebe als Akkumulationsindikator. Gefahrstoffe – Reinhaltung der Luft 56, 8: 351 – 357.
- **Tilley, D.R., 2011.** Effects of vertical vegetation on thermal balance of buildings. Webinar organised by Green roofs for healthy cities, 2011.
- **TNO, 2006.** Fysiologische en psychische en gezondheidseffecten van planten in de werksituatie op de gezondheid en welbevinden van werknemers. TNO Hoofddorp, 2006.
- **Tonneijck, A.E.G., Blom-Zandstra, M., 2002.** Landschapselementen ter verbetering van de luchtkwaliteit rond de ruit van Rotterdam. Plant Research International B.V., Wageningen, Nota 152.
- **Ulrich, R.S., Simons, R.F., Losito, B.D., 1991.** "Stress recovery during exposure to natural and urban environments." Journal of Environmental Psychology, 1991, 11; p201-230 ed.
- **Ulrich, R., 1984.** View through a window may influence recovery from surgery. Science 224, pp. 420–421.
- **United Nations, Economic and Social Council, 2007.** Recent results on corrosion trends and the protection of cultural heritage from air pollution. ECE/EB.AIR/WG.1/2007/8.
- **Vermeulen, A.T., Kraai, A., Duyzer, J.H., Klok, E.J., Pronk, A.A., 2009.** Vegetatie langs wegen en luchtkwaliteit. Rapportage IPL, ECN rapportnr ECN0O—09-016.
- **Wesseling, J.P., Duyzer, J., Tonneijck, A.E.G., van Dijk, C.J., 2004.** Effecten van groenelementen op NO2 en PM10 concentraties in de buitenlucht. TNO Milieu, Energie en Procesinnovatie, Apeldoorn. R2004/383.
- **Weijers, E.P., Even, A., Kos, G.P.A., Groot, A.T.J., Erisman, J.W., Brink, H.M., 2001.** Particulate matter in urban air: health risks, instrumentation and measurements, and political awareness. ECN-R-01-002
- **Wesely, M., L., 1989.** Parameterization for surface resistance to gaseous dry deposition in regional scale numerical models. Atmospheric Environment 23:1293–1304.
- **Whitford, V., Ennos, A.R., Handley, J.F., 2001.** City form and natural process-indicators for the ecological performance of urban areas and their application to Merseyside, UK. *Landscape and Urban Planning 57, 91-103.*

- **Wilson, E., Biophilia, O., 1984.** Cambridge: Harvard University Press, 1984, ISBN 0-674-07442-4.
- **Wong, Nyuk Hien, and Alex Yong Kwang Tana., 2010.** "Acoustics evaluation of vertical greenery systems for building walls." Building and Environment (Department of Building, School of Design and Environment, National University of Singapore) Volume 45, no. Issue 2 (2010): 411-420.
- **Wong N.H., et al., 2009.** Thermal evaluation of vertical greenery systems for building walls, Building and Environment, doi:10.1016/j.buildenv.2009.08.005.
- **Lambertini, A., 2007.** Vertical gardens: bringing the city to life. Thames and Hudson, London, 2007. ISBN 978-0-500-51369-9.
- **Laurie, I.C., 1977.** Nature in cities, the natural environment in the design and development of urban green space. John Wiley & Sons Ltd. ISBN 0 471 99605 X.
- **NEN-EN-ISO 6946:2008.** Building components and building elements - Thermal resistance and thermal transmittance - Calculation method (ISO 6946:2007, IDT).
- **Ottelé M. Van Bohemen H., Fraaij, A.L.A., 2010.** Quantifying the deposition of particulate matter on climber vegetation on living walls, Ecological Engineering 36 154-162.
- **Van Dale dictionary of the Dutch language 14, 2005.**
- **Stainless steel solutions, 2010.** Maintenance of green façades, http://www.s3i.co.uk/greenwallmaintenance.php
- http://www.epa.gov/air/airpollutants.html
- http://www.rivm.nl/milieuportaal/images/14_hb_BINNENMILIEU
- http://213.154.245.57/bouwbesluitonline/default.aspx?AspxAutoDetectCookieSupport=1
- http://www.greenroofs.org

Summary

Planting on roofs and façades is one of the most innovative and fastest developing fields of green technologies with respect to the built environment and horticulture. This thesis is focused on vertical greening of structures and to the multi-scale benefits of vegetation. Vertical green can improve the environment in urban areas and is becoming a key design consideration in modern building developments. Vertical greening of structures offers large surfaces with vegetation and at the same time contribute to the improvement of the thermal behaviour of buildings, increased biodiversity, aesthetical and social aspects but also reduction of air polluting substances as fine dust, carbon dioxide, etc.

There are different concepts of vertical green to vegetate the exterior building envelope; two major categories can be considered namely: green façades and living walls. Green façades are made up of climbing plants either growing directly on a wall or, more recently, growing indirectly against a wall with specially designed supporting structures, such as grids, trellis or meshes. Living wall systems (LWS) are composed of pre-vegetated panels or integrated fabric systems that are affixed to a structural wall or frame, whereas a hydroponical system is required to maintain plant growth. Living wall systems (LWS) is a relative new technology and rarely investigated yet.

One of the multi-scale benefits of vegetation is the accumulation of fine dust particles on leaf surfaces. Dust particles smaller than 10 μm are mainly relevant in dense urban areas, because they can be deeply inhaled into the respiratory system and cause damages for the human health. Results found during the doctoral study confirm the relation between particle origin, compound and particle number between different environments as the woodland and near a traffic road. Using image analyzing software on electron microscope images as shown in the thesis enables to study and examine dust particles directly on leaves; it is a process which is able to identify particle size and number. The productive approach contrasts with past research methods that identified dust concentration on tree leaves through washing or leaching of leaves to determine particle mass.

Another important aspect of vertical greening is related to the thermal comfort and behaviour of buildings. The thermal transmittance (and thus insulation properties as well) of a building is among other things dependant by the wind velocity that passes the surface of the building. A study conducted for different greening systems shows the potential of vertical green layers on reducing the wind velocity along building façades. In the case of living wall systems the insulation properties of the materials used can be taken into account, as well as the air cavity between the system and the façade as proofed with the calculations.

In order to study the effect of a green layer on the temperature gradient through a façade better, an experimental set-up was built (climate chambers). The experimental set-up as used, allows controlled measurements with different boundary conditions (temperatures), besides the measurements are repeatable

and reproducible. The results show that especially the living wall systems have a positive effect on the thermal behaviour of buildings.

Greening of the building envelope with living wall systems considering the materials involved, can has a high influence on the environmental profile (life cycle analysis) as shown in the thesis. Although applying vertical green is not a new concept, it can offer multiple benefits as a component of current urban design. Considering the relation between the environmental benefits, energy saving for the building and the vertical greening systems (material used, maintenance, nutrients and water needed) the integration of vegetation could be a sustainable approach (taking into account all the unquantifiable benefits until now) for the envelope of new and existing buildings.

Zusammenfassung

Das Einpflanzen auf Dächern und Fassaden ist eines der innovativsten und am schnellsten entwickelnden Bereiche der grünen Technologien in Bezug auf die gebaute Umwelt und Gartenbau. Diese These konzentriert sich auf vertikale Begrünung von Bauwerken und den Multi-Skalenvorteile der Vegetation. Vertikales Grünen kann zur Verbesserung der Umwelt in städtischen Gebieten beitragen und wird zu einer Schlüsseldesign-Überlegung in modernen Gebäudeentwicklungen. Vertikale Begrünung von Bauwerken bietet große Flächen mit Vegetation und gleichzeitig einen Beitrag zur Verbesserung des thermischen Verhaltens von Gebäuden, Verbesserung der Artenvielfalt, ästhetische und soziale Aspekte, aber auch Reduktion der Luftschadstoffe wie Feinstaub, Kohlendioxid, etc.

Es gibt verschiedene Konzepte des vertikalen Grüns um nach außen die Gebäudehülle zu vegetieren; zwei Hauptkategorien können nämlich [or: namentlich] in Betracht gezogen werden: Grüne Fassaden und lebende Wände. Grüne Fassaden sind aus Kletterpflanzen gemacht; entweder wachsen sie direkt an einer Wand oder in jüngerer Zeit zunehmend indirekt gegen eine Wand, mit speziell kreierten Tragwerken, wie Gitter, Spalier oder Netze. Lebende Wandsysteme (LWS) bestehen aus bereits bewachsenen Platten oder Geweben, die auf einer strukturellen Wand oder ein Rahmen befestigt sind, während ein hydroponisches System benötigt wird, um das Pflanzenwachstum beizubehalten. Lebende Wandsysteme (LWS) sind eine relativ neue Technologie und noch wenig untersucht.

Einer der Multi-Skalen-Vorteile der Vegetation ist die Ansammlung von Feinstaub auf Blattoberflächen. Staubpartikel kleiner als 10 μm sind vor allem relevant in dicht besiedelten städtischen Gebieten, weil sie tief in die Atemwege eindringen und Gesundheitsschäden für den Menschen verursachen können. Die Ergebnisse während des Promotionsstudiums bestätigen den Zusammenhang zwischen Teilchenherkunft und (chem.) Verbindung und zwischen Teilchenzahl und verschiedenen Umgebungen wie der Wald und in der Nähe einer befahrenen Straße. Wie in der Arbeit gezeigt, ermöglicht das Auswerten von elektronenmikroskopischen Aufnahmen mittels einer Bild-Analyse-Software das Studieren und Untersuchen von Staubteilchen direkt auf den Blättern; es handelt sich dabei um ein Prozess, welcher in der Lage ist Teilchengröße und -zahl zu ermitteln. Der produktive Ansatz steht im Gegensatz zu der Methodik in früheren Forschungsarbeiten, die Staubkonzentration an Baumblättern durch Waschen oder Auslaugen von Blättern zu Partikelmasse identifizierten.

Ein weiterer wichtiger Aspekt der vertikalen Begrünung steht im Zusammenhang mit der thermische Behaglichkeit und das Verhalten von Gebäuden. Der Wärmedurchgangskoeffizient (und damit auch Dämmeigenschaften) eines Gebäudes ist unter anderem durch die Windgeschwindigkeit, die die Oberfläche des Gebäudes passiert, abhängig. Eine Studie, die für verschiedene Begrünungssysteme durchgeführt wurde, zeigt das Potenzial von vertikalen grünen

Schichten auf die Reduzierung der Windgeschwindigkeit entlang der Fassaden. Im Fall von lebenden Wandsysteme können die Dämmeigenschaften der verwendeten Materialien berücksichtigt werden sowie die Luftschicht zwischen dem System und die Fassade als Bewiesen mit den Berechnungen.

Um die Wirkung einer grünen Schicht auf dem Temperaturgradient durch eine Fassade besser zu studieren, wurde ein experimentelles Set-Up gebaut (Klimakammer). Der experimentelle Aufbau ermöglicht kontrollierte Messungen mit unterschiedlichen Randbedingungen (Temperaturen); außerdem sind die Messungen wiederholbar und reproduzierbar. Die Ergebnisse zeigen, dass vor allem die lebenden Systeme einen positiven Effekt auf das thermische Verhalten von Gebäuden haben.

Ökologisierung der Gebäudehülle mit lebenden Wandsysteme unter Berücksichtigung der beteiligten Materialien, kann, wie in der Arbeit gezeigt, einen hohen Einfluss auf die Umweltverträglichkeit (Life Cycle Analysis) haben. Obwohl die Anwendung von vertikalem Grün kein neues Konzept ist, kann es mehrere Vorteile als Bestandteil des aktuellen urbanen Designs anbieten. Betrachtet man die Beziehung zwischen dem Nutzen für die Umwelt, Energieeinsparung für das Gebäude und die vertikale Begrünungssysteme (Material, Wartung, erforderliche Nährstoffe und Wasser), könnte die Integration von Vegetation (unter Berücksichtigung aller quantifizierbaren Vorteile bis jetzt) ein nachhaltiger Ansatz für die Hülle von neuen und bestehenden Gebäuden werden.

Riepilogo

Fra le tecnologie verdi per l'ambiente costruito e l'orticultura l'inverdimento di coperture e facciate è uno dei sistemi più innovativi e di rapido sviluppo. Questa tesi è focalizzata su sistemi per il verde verticale e sui benefici della vegetazione a diverse scale. Il verde verticale può migliorare il benessere ambientale delle aree urbane e sta diventando un elemento chiave nello sviluppo del costruito moderno. L'inverdimento verticale di strutture offre alla vegetazione ampi spazi verdi e allo stesso tempo contribuisce al miglioramento del comportamento del costruito, all'aumento della biodiversità, ha degli effetti in senso sociale e psicologico e permette la riduzione di inquinanti come polveri sottili, anidride carbonica, etc.
Esistono diversi sistemi per l'inverdimento dell'involucro verticale; possono essere classificati in: facciate verdi e sistemi living walls (giardini verticali). Le facciate verdi sono costituite da rampicanti che crescono direttamente sulla facciata o davanti alla facciata supportati da strutture come griglie, cavi, reti. I sistemi living wall (LWS) sono costituiti da pannelli pre-vegetati o sistemi integrati, fissati ad un muro strutturale o ad un telaio, con cultura idroponica per la crescita delle specie vegetali. La tecnologia dei sistemi living wall è relativamente nuova e non molto studiata.

Uno dei benefici, a diverse scale, della vegetazione riguarda l'accumulo di particelle di polveri sottili sulla superficie delle foglie. Le particelle più piccole di 10 μm, presenti in particolare nelle aree urbane, possono causare dei danni alla salute, perché possono essere profondamente inalati dal sistema respiratorio. I risultati ottenuti durante la ricerca di dottorato confermano la relazione tra l'origine, la composizione ed il numero di particelle ed i diversi ambienti, come aree rurali e zone vicino a strade trafficate. Grazie all'uso di un software analitico sul microscopio elettronico le immagini, come dimostrato nella tesi, hanno permesso di studiare ed esaminare le poveri sottili direttamente sulle foglie e di identificare la grandezza ed il numero delle particelle. Quest'approccio è in contrasto con I precedenti metodi di ricerca che identificavano la concentrazione di poveri sottili con il lavaggio delle foglie per determinare la massa delle particelle.

Un altro aspetto importante del verde verticale riguarda il comfort termico e il comportamento degli edifici. La trasmittanza termica (e quindi la capacità isolante) di un edificio dipende, fra le altre cose, dalla velocità del vento sulle facciate degli edifici. Uno studio condotto per diversi sistemi di verde verticale mostra la potenzialità della pelle verde nella riduzione della velocità del vento intorno alla facciata. Nel caso dei sistemi living wall può essere considerata anche la capacità isolante degli altri materiali usati come anche la camera d'aria fra il sistema e la facciata, come dimostrato.

Per studiare l'effetto di uno strato vegetato sul gradiente termico attraverso una facciata è stato realizzato un esperimento (camera climatica). L'esperimento permette di effettuare misurazioni con diverse situazioni limite (temperature), oltre al fatto che le misurazioni sono ripetibili e riproducibili. I risultati mostrano che in

particolare i sistemi living wall hanno un effetto positivo sul comportamento termico degli edifici.
L'inverdimento dell'involucro edilizio con sistemi living wall, considerando i materiali coinvolti,può avere una elevata influenza sul profilo ambientale (life cycle analysis), come mostrato nella tesi. Inoltre applicare il verde verticale, nell'attuale progettazione urbana, non è una nuova tecnica e permette di ottenere molti benefici come componente. Considerando la relazione tra i benefici ambientali, il risparmio energetico per l'edificio e il sistema per il verde verticale (materiali usati, mantenimento, nutrienti ed acqua necessari), l'integrazione di vegetazione può essere un approccio sostenibile (considerando tutti i benefici non ancora quantificabili) per l'involucro di nuove costruzioni e per edifici esistenti.

Samenvatting

Het vergroenen van daken en gevels is één van de meest innovatieve en snelst ontwikkelende gebieden van duurzame technologieën met betrekking tot de bebouwde omgeving en tuinbouw. Dit proefschrift richt zich op verticale vergroening van gebouwen en de bijbehorende multifunctionele voordelen van vegetatie.
Verticaal groen draagt bij aan verbetering van het milieu in stedelijke gebieden en is steeds meer een belangrijke overweging bij het ontwerp en ontwikkelen van moderne gebouwen. Verticale vergroening van gebouwen biedt grote oppervlakken met vegetatie en daarnaast draagt het bij aan de verbetering van het thermisch gedrag van gebouwen, toenemende biodiversiteit, esthetische en sociale aspecten, maar ook tot vermindering van luchtverontreinigende stoffen zoals fijn stof deeltjes, koolstofdioxide, etc.

Er zijn verschillende verticaal groen concepten te onderscheiden als buitentoepassing voor de gebouwenschil, echter twee hoofdcategorieën kunnen worden beschouwd namelijk: groene gevels en living wall systemen. Groene gevels zijn begroeid door klimplanten, hetzij rechtstreeks groeiend tegen een muur of indirect groeiend met daarvoor speciaal ontworpen hulpconstructies, zoals spandraden, tralie- of gaas. De living wall systemen (LWS) bestaan uit geïntegreerde of prefab systemen die zijn aangebracht op een constructie of hulpframe waarin de planten wortelen. Daarnaast is een watergeefsysteem met voedingsstoffen noodzakelijk om ervoor te zorgen dat de groene gevel blijft bestaan. De living wall systemen zijn een vrij nieuwe technologie die nog steeds in ontwikkeling is en waaraan nog zelden onderzoek aan is verricht.

Eén van de multifunctionele eigenschappen van de vegetatie is de accumulatie van fijne stofdeeltjes op bladoppervlakken. Stofdeeltjes kleiner dan 10 μm zijn voornamelijk relevant in dichtbevolkte stedelijke gebieden, omdat ze diep in de luchtwegen ingeademd worden en veroorzaken zo schade aan de gezondheid van de mens. Resultaten gevonden tijdens het promotieonderzoek bevestigen de relatie tussen deeltjes herkomst, hoeveelheid en samenstelling tussen verschillende milieus bijvoorbeeld bladeren uit een bosrijke omgeving en bladeren naast een verkeersweg. Met behulp van de ontwikkelde methode op basis van beeld bewerkingssoftware en elektronenmicroscoop opnamen, maakt het mogelijk om rechtstreeks fijn stofdeeltjes op de bladeren te onderzoeken, het is tevens een methode welke in staat is om de deeltjesgrootte en het aantal deeltjes te identificeren. De productieve benadering staat in contrast met onderzoeksmethoden uit het verleden, die erop gericht waren om de massa concentratie van fijn stof op bladeren van bomen door middel van wassen of uitspoeling te bepalen.

Een ander belangrijk aspect van verticaal groen is gerelateerd aan het thermisch comfort en het gedrag van gebouwen. De warmtedoorgangscoëfficiënt (en dus bijbehorende isolatie-eigenschappen) van een gebouw is onder andere afhankelijk van de erlangs strijkende windsnelheid. Metingen uitgevoerd voor verschillende verticaal groensystemen toont het potentieel van de verticale groene lagen op het verminderen van de windsnelheid langs gevels. In het geval van living wall systemen (LWS) mogen de isolerende eigenschappen van de gebruikte materialen in aanmerking worden genomen, evenals de gecreëerde luchtspouw tussen living wall systeem en de gevel.

Om het effect van verticaal groensystemen op het verloop van de temperatuurgradiënt door een gevel beter inzichtelijk te maken, is er een proefopstelling opgebouwd (klimaatkamers). De experimentele opgezet zoals gebruikt, staat gecontroleerde metingen met verschillende randvoorwaarden (temperaturen) toe, daarnaast zijn de metingen herhaalbaar en reproduceerbaar. De verkregen resultaten tonen aan dat vooral de living wall systemen een positief effect op het thermisch gedrag van gebouwen hebben, maar ook dat de totale thermische massa van een gevel hierin betrokken dient te worden.

Vergroening van de gebouwenhuid met living wall systemen, overwegende de betrokken materialen, heeft een sterke invloed op de milieubelasting (life cycle analysis), zoals weergegeven in het proefschrift. Hoewel de toepassing van verticaal groen geen nieuw concept is, kan het meerdere voordelen bieden en functioneren als een onderdeel van huidig stedenbouwkundig ontwerp. Gelet op de verhouding tussen de voordelen en nadelen voor het milieu, energiebesparing voor het gebouw en het gekozen verticaal groensysteem (gebruikte materialen, onderhoud, voedingsstoffen, water, etc.) kan de integratie van vegetatie op bestaande en nieuwe gebouwen leiden tot een duurzame ontwikkeling.

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Curriculum Vitae

Name:	Marc Ottelé
Date of birth:	5 December, 1979
Place of birth:	Rotterdam, the Netherlands

2000 – 2007 Bachelor and Master student in Civil Engineering student, specialisation Structural Engineering, Faculty of Civil Engineering and Geosciences, Delft University of Technology, The Netherlands.

2007 – 2011 PhD researcher, Delft University of Technology, faculty of Civil Engineering and Geosciences, department Materials & Environment, section Sustainability.

2011 – heden

List of publications related to the thesis

Ottelé, M., Bohemen, H.D., van, Fraaij, A.L.A., (2009). Ecological Engineering; green roofs and the greening of vertical walls of buildings. Landscape architecture, 1, 042-049 & Proceedings of Ecocity 2008, Mexico.

Ottelé, M., Fraaij, A.L.A., Bohemen, H.D. (2008). Quantifying the effect of living walls on reduction of particulate matter (PMx) by deposition on vegetation. In s.n. (Ed.), 1st international conference on BioGeoCivil engineering (pp. 1-10), Delft, The Netherlands.

Ottelé, M., Bohemen, H.D. van. (2009) Begroeid Beton. Cement, vol 3.

Ottelé, M., Bohemen, H.D. , Fraaij, A.L.A. (2010) Quantifying the deposition of particulate matter on climber vegetation on living walls. Published in Journal of Ecological Engineering 36 (2010) 154-162.

Ottelé, M., (2010). The design of vertical greened surfaces - a technical approach. In s.n. (Ed.), 3. FBB-Symposium Fassadenbegrunung 2010 (pp. 20-25). Berlin, Fachvereinigung Bauwerksbegrunung e.V. (FBB).

Ottelé, M., Koleva, D.A., Breugel, K., van., Haas, E.M., Fraaij, A.L.A., Bohemen, H.D. (2010) Concrete as a multifunctional ecological building material - A new approach to green our environment. International symposium Ecology and Safety Vol. 4. Journal of international scientific publications: Ecology and Safety (pp. 223-234). Bulgaria.

Ottelé, M., Perini, K., A.L.A. Fraaij, Haas, E.M., Raiteri, R. (2011) Comparative life cycle analysis for green façades and living wall systems. Published in the 20th International Symposium of Ecology and Safety 2011, volume 5.

Perini, K., Ottelé, M., A.L.A. Fraaij, Haas, E.M., Raiteri, R. (2011) Vertical green systems and their effect on air flow and temperature near the façade. Published in Building and Environment, 2011. doi: 10.1016/j.buildenv.2011.05.009.

Ottelé, M., Ursem, W.N.J., Fraaij, A.L.A., Bohemen, H.D. (2011) The development of an ESEM based counting method of fine dust particles and a philosophy behind the background of particle adsorption on leaves. Accepted Air Pollution 2011

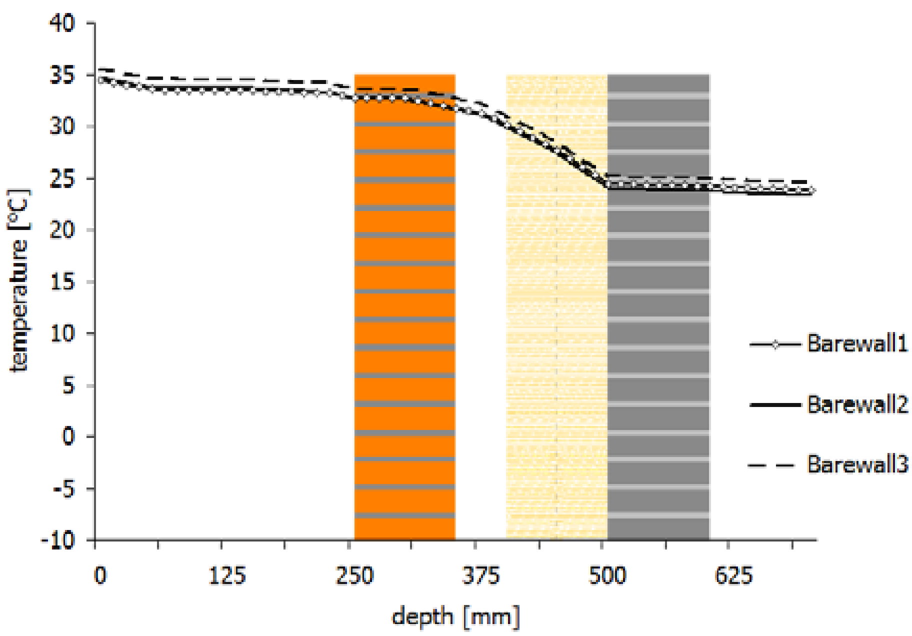
Ottelé, M., Mir, M.A., Guiberti, T., Fraaij, A.L.A., Bohemen, H.D., (2011) Comparing ivy (Hedera helix) leaves with different materials on PMx adsorption capacity, using an ESEM based counting method. Article in press journal of Civil Engineering and Architecture.

Perini, K., Ottelé, M., Haas, E.M., Raiteri, R. (2011) Greening the building envelope, façade greening and living wall systems. Accepted Open Journal of Ecology (OJE), 2011.

Ottelé, M., Mir, M.A., Fraaij, A.L.A., Bohemen, H.D., E.M. Haas. (2011). Experimental approach to investigate the thermal behaviour of vertical greened façades of buildings. Submitted to journal of Urban Ecosystems 2011

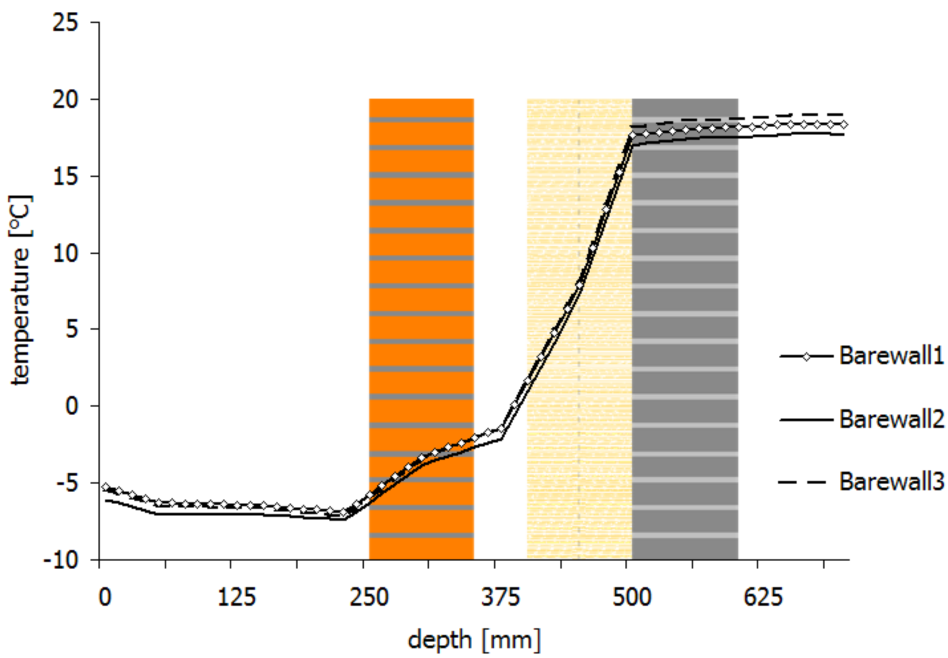
Appendix A Summer measurements bare wall

Validation bare wall											
time (hours)	measuring points summer temperature (°C)										
	$T_{ext.}$	T_{green} surface	T_{middle} foliage	$T_{substrate}$	T_{air} cavity	$T_{ext.}$ surface (outside)	T_{cavity}	$T_{surface}$ insulation	$T_{int.\ surface}$ (inside)	$T_{int.\ surface}$ (outside)	$T_{int.}$
$t_{bare\ wall1;\ 0}$	25.28	--	--	--	--	24.17	24.06	23.76	23.30	23.56	24.02
$t_{bare\ wall2;\ 0}$	23.78	--	--	--	--	22.85	22.85	23.17	23.09	22.97	23.40
$t_{bare\ wall3;\ 0}$	26.75	--	--	--	--	24.61	24.50	24.47	24.37	24.26	24.12
$t_{bare\ wall1;\ 1}$	34.25	--	--	--	--	26.22	24.73	24.47	23.75	24.01	24.02
$t_{bare\ wall2;\ 1}$	33.69	--	--	--	--	27.23	24.12	24.11	23.15	23.13	23.45
$t_{bare\ wall3;\ 1}$	35.35	--	--	--	--	27.14	25.59	25.29	24.53	24.35	24.12
$t_{bare\ wall1;\ 2}$	34.98	--	--	--	--	27.62	26.06	25.58	23.84	24.01	24.02
$t_{bare\ wall2;\ 2}$	33.87	--	--	--	--	28.64	26.06	26.16	23.25	23.07	24.13
$t_{bare\ wall3;\ 2}$	34.32	--	--	--	--	28.33	26.10	26.10	24.51	23.80	23.95
$t_{bare\ wall1;\ 4}$	34.50	--	--	--	--	30.02	28.31	27.49	24.11	24.01	24.02
$t_{bare\ wall2;\ 4}$	34.60	--	--	--	--	30.45	29.70	28.85	23.46	23.30	23.22
$t_{bare\ wall3;\ 4}$	35.54	--	--	--	--	30.40	29.17	28.32	24.74	24.51	24.18
$t_{bare\ wall1;\ 8}$	34.84	--	--	--	--	32.63	31.29	30.10	24.54	24.25	24.13
$t_{bare\ wall2;\ 8}$	34.62	--	--	--	--	32.57	31.08	29.85	24.02	23.78	23.36
$t_{bare\ wall3;\ 8}$	35.52	--	--	--	--	33.63	32.21	30.99	25.19	24.96	24.58



Appendix B Winter measurements bare wall

Validation bare wall											
Time (hours)	measuring points winter temperature (°C)										
	$T_{ext.}$	T_{green} surface	T_{middle} foliage	$T_{substrate}$	T_{air} cavity	$T_{ext.}$ surface (outside)	T_{cavity}	$T_{surface}$ insulation	$T_{int.\ wall}$ surface (inside)	$T_{int.\ surface}$ (outside)	$T_{int.}$
$t_{bare\ wall1;\ 0}$	24.16	--	--	--	--	24.43	24.40	24.32	23.44	23.98	23.49
$t_{bare\ wall2;\ 0}$	23.72	--	--	--	--	24.01	23.93	23.86	23.69	23.57	22.99
$t_{bare\ wall3;\ 0}$	24.88	--	--	--	--	25.16	25.13	25.05	24.85	24.70	24.90
$t_{bare\ wall1;\ 12}$	2.61	--	--	--	--	5.20	10.93	12.98	23.24	23.37	22.95
$t_{bare\ wall2;\ 12}$	2.10	--	--	--	--	5.21	10.47	12.53	22.79	22.89	23.64
$t_{bare\ wall3;\ 12}$	2.90	--	--	--	--	5.36	11.25	13.37	23.94	24.07	22.52
$t_{bare\ wall1;\ 24}$	0.20	--	--	--	--	0.12	4.73	7.50	21.54	21.85	21.58
$t_{bare\ wall2;\ 24}$	-1.87	--	--	--	--	-0.52	4.05	6.84	21.01	21.33	21.06
$t_{bare\ wall3;\ 24}$	0.25	--	--	--	--	0.12	4.88	7.72	22.19	22.51	22.22
$t_{bare\ wall1;\ 48}$	-4.74	--	--	--	--	-5.27	-0.82	2.35	19.61	19.07	19.07
$t_{bare\ wall2;\ 48}$	-4.88	--	--	--	--	-5.20	-0.82	2.32	18.17	18.63	18.60
$t_{bare\ wall3;\ 48}$	-4.85	--	--	--	--	-5.43	-0.84	2.42	19.77	19.65	19.64
$t_{bare\ wall1;\ 72}$	-7.62	--	--	--	--	-6.64	-2.35	0.81	17.05	17.65	17.85
$t_{bare\ wall2;\ 72}$	-7.63	--	--	--	--	-6.84	-2.42	0.80	16.58	17.14	17.38
$t_{bare\ wall3;\ 72}$	-7.19	--	--	--	--	-6.62	-2.32	0.84	17.56	18.18	18.39



Appendix C Specifications related to the climate chamber

Specifications used hot gun
GH-GW-1500A
1500W 230V 50Hz
POS.I max. 300 °C 280 L/min
POS.II max. 500 °C 480 L/min

Specifications Advantech 4718, 8-channel Thermocouple Input USB Module
Analog Input
Accuracy ±0.1% for voltage input
Channels 8 differential
Resolution 16 bits
Sampling Rate 10 S/s (total)
Span Drift ±25 ppm/° C

T/C Type and Temperature Ranges

J	0 ~ 760° C	R	500 ~ 1750° C
K	0 ~ 1370° C	S	500 ~ 1750° C
T	-100 ~ 400° C	B	500 ~ 1800° C
E	0 ~ 1000° C		

Zero Drift ±0.3 μV/° C

Specifications NI USB-6211 16-Bit, 250 kS/s M Series Multifunction DAQ
Analog Input
Channels 16, 8
Single-Ended Channels 16
Differential Channels 8
Resolution 16 bits
Sample Rate 250 kS/s
Minimum Voltage Range Sensitivity 4.8 μV

Specifications ENDA ET1411 DIGITAL THERMOSTAT temperature controller
Supply voltage 230V AC +10% -20%, 50/60Hz or 12/24V AC/DC ±10%, 50/60Hz.
Power consumption Max. 3VA
Wiring 2.5mm² screw-terminal connections
Scale -60.0 ... +150.0°C (-76.0 ... +302.0°F)
Sensitivity/Accuracy 0.1°C / ±1°C
Time Accuracy (±1%-1sec)