QUALITY-ASSURED SOLUTIONS FOR VEGETATIVE (GREEN) ROOF SYSTEMS ON CONCRETE DECKS

C.-M. Capener[1], Y. Edwards[2], T. Emilsson[3], J. Malmberg[4] & A. Pettersson Skog[5]
[1]SP Technical Research Institute of Sweden, Borås, Sweden
[2]Swedish Cement and Concrete Research Institute, Stockholm, Sweden
[3]Swedish University of Agricultural Sciences, Alnarp, Sweden
[4]Scandinavian Green Roof Institute, Malmö, Sweden
[5]Sweco Environment, Stockholm, Sweden

ABSTRACT

Vegetative (green) roof systems and eco-neighborhoods with gardens on concrete decks are for many reasons being prescribed today around the world and increasingly so in major Swedish cities. However, in Sweden and other countries, there is a lack of knowledge, experience, standards and guidelines as well as collaboration between stakeholders when installing such systems. It is incredibly important to avoid any leakage during the lifetime of a vegetative (green) roof system but this cannot be completely guaranteed with today's installation practice and project management.

This paper presents a selection of the final results from a Swedish collaborative project aiming at bringing together researchers, government and industry to cooperatively develop new and attractive solutions for vegetative (green) roof systems on concrete decks with consideration to the environment and high requirements for durability, materials, construction and energy efficiency. Special attention is given to the impact of the vegetative (green) roof systems on concrete structures in terms of design loads and moisture management. Requirements for quality assurance are placed both on the concrete structure as well as the vegetative superstructure.

Keywords: Vegetative (green) roof systems, guidelines, concrete decks, waterproofing.

1. Introduction

Vegetative (green) roof systems and eco-neighborhoods with gardens on concrete decks must be carefully built-up and quality assured with regards to waterproofing to protect building contents as well as protecting structural integrity. Waterproofing systems are commonly placed on top of concrete decks to prevent moisture from entering the building structure. Such systems normally include a root barrier to prevent root penetration through the waterproofing layer and subsequently also leakages. In Sweden, thermal insulation is installed together with the waterproofing and root barrier. Finally, the vegetative superstructure is installed using a combination of several technical solutions including selected plant materials, engineered vegetation substrates, drainage layers and geotextiles. A carefully planned and executed vegetative (green) roof system will ensure long term performance, structural integrity of the building envelope and reduced maintenance. Often, the purpose and design of a green roof is to supply added values such as different urban ecosystem services, Figure 1. Such services span over different qualities, covering environmental value (E), social value (S) and climate adaptation (C). Included are:

- Increased biodiversity or preservation of local plants (E)
- Provision of new recreation space (S)
- Contribution to stormwater management by water retention and evapotranspiration (E, C)
- Provision of temperature moderating effects, i.e. reducing urban heat island effects (C)
- Providing energy savings (depending on local climate conditions and building structure) (E, C)
- Noise reduction (S)

Fig. 1. Vegetative (green) roof system in Malmö, Sweden. This rooftop garden at a shopping center is open to visitors for recreation and provides several ecosystem services.

This paper presents a selection of final results from a Swedish collaborative project, including some nineteen participating partners (Edwards, 2014), aiming at bringing together researchers, government and industry to cooperatively develop new and attractive solutions for vegetative (green) roof systems on concrete decks under Scandinavian climatic conditions. The project result is expected to raise industry standard, improve quality assurance, and lead to attractive and durable solutions in the international forefront of vegetative (green) roof systems on concrete decks. At normal maintenance and care, given proper material selection and installation, the ambition of the collaborative project is to provide guidance ensuring green roof systems to have a service life of 100 years.

2. The design, planning, construction and maintenance of green roofs

When planning and building green roofs, there are many stakeholders involved and it is very easy to miss some information in this communication jungle. The intention of this project (including the development of guideline, handbooks, manuals and checklists) therefore has been to make sure that all parties involved in planning and building green roofs should get an understanding of what is required to achieve a successful outcome.

When designing a green roof, it is important to know exactly what the intended use is meant to be for the roof. Green roof design may vary significantly depending on the function required. The project handbook for green roofs' vegetative superstructures (Pettersson Skog, 2016) focuses on the intended use and aim of the roof. Intended use influences the choice of vegetation, which in turn will have great significance on the choice and requirements of all underlying layers and components such as plant bed, drainage, waterproofing and concrete deck during design and construction. How different factors are interrelated and influence each other is illustrated in Figure 2.

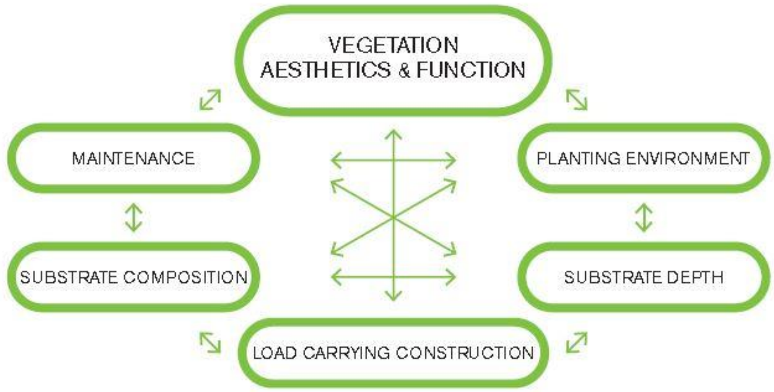

Fig. 2. Factors and relationships affecting the vegetative superstructures' appearance, durability and function but also the concrete structure, e.g. load carrying capacity. Changes in one factor may have great impact on other factors and on the system as a whole.

For a successful green roof installation, information and communication is of fundamental importance. Above all, there should be a clear picture or idea of what you want the green roof to deliver in form of appearance of alternative social value (S), ecological function (E) or climate adaptation qualities (C). A roof which is primarily installed for stormwater management, for example, may look very different compared to one that will serve as recreational space for tenants in an apartment block. For a successful outcome, the functions that the green roof should deliver need to be discussed along with the level and extent of considered maintenance levels of the vegetative surfaces.

3. Benefits from green roofs

There are many advantages to using vegetated (green) roof systems and gardens in cities that are often highlighted. From an ecological point-of-view, green roofs create new opportunities for life inside the cities and have a positive impact on biodiversity.

3.1 Biodiversity

Vegetative (green) roof systems is a part of the city's green infrastructure and can as such form habitat for local plants that may have disappeared during previous densification of cities. The current densification trend is putting increased pressure on existing green structures, and green roofs are in this framework a possibility to create a dense city with green qualities. The design of green roofs for biodiversity will influence the habitat use of plants and animal species. Scientific evidence shows that proper design of green roofs for biodiversity have the potential to even support red-listed species (Brenneisen, 2006). Biodiversity is a prerequisite for the resilience of ecosystems, e.g. due to climate change, because it involves a proliferation of risks and greater opportunity for reorganization after a disturbance in an ecosystem. It is also important that the green roof design for biodiversity is linked to the local biodiversity policy of a city or region.

3.2 Stormwater management

Another major environmental benefit of green roofs is in stormwater management, an advantage that is often mentioned in the justification for the choice of green roofs. By planting vegetation on roofs, some of the rainwater is absorbed by vegetation and substrate and then evaporated back to the atmosphere.

This helps to delay stormwater and reduce the pressure on the city's stormwater system. Different types of green roofs have different delay capacity. A number of studies show that green roofs can reduce annual runoff with 40-90 % depending on the depth of the substrate, and delay the flow of up to 30 minutes (Li, 2014). This is dependent on the green roof design and construction; substrates, plant depth, plant varieties and roof inclination.

3.3 Resiliens to climate change and urban heat island effect

The trend of global heating and the increasing temperature of cities put stress on its inhabitants. Green roofs have the possibility to change the energy balance of cities due to increased reflection and increased latent cooling by evapotranspiration from plants and substrates, counteracting the heat-absorbing (and radiative) effect found in non-green, solid surfaces, which contributes to higher urban temperatures, so-called urban heat islands. Vegetation also consumes carbon dioxide for photosynthesis and contributes to a carbon sink.

By moisture returning to the atmosphere through substrate evaporation and plants' transpiration, solar heat load on roof surfaces can be reduced. Also, the vegetation reflects more solar radiation than a traditional roof surface which adds to the cooling effect described above (Takebayashi, 2007).

3.4 Other benefits from green roofs

The cooling effect by evaporation from the green roof, combined with an increased thermal mass by the substrate and green roof superstructure, can in some cases reduce the cooling requirements of a building and the corresponding saved carbon dioxide emissions from the energy source for air conditioning. Additionally, green roofs contribute to sound absorption and reduce noise effects from the urban environment. Properly designed green roofs can also provide valuable recreational areas, contributing to a social quality.

4. Addressing the increased interest in vegetated (green) roofs and gardens

In Sweden, we see an increased interest from developers and property owners to build and manage buildings with vegetated (green) roofs and gardens. With the increasing interest, the need to build knowledge increases regarding quality assurance of green roofs in order to build sustainable and well-functioning systems. It is incredibly important to avoid any leakage during the lifetime of a vegetative (green) roof system but this cannot be completely guaranteed with today's installation practice and project management.

Starting in 2013, a Swedish collaborative project started to address these issues. The project was divided in several working groups focusing on different aspects of green roofs and also included several case studies where the design and construction processes were studied. Two handbooks and a guideline for developers and designers is the outcome of the project. Below are some selected results from the handbooks, one focusing on the vegetation system and landscaping, and the other on the waterproofing system, insulation and concrete deck. Requirements for quality assurance are placed both on all components included.

The working group studying some Swedish green building cases emphasized the need to include all stakeholders early in the process and to clarify important mile stones in the planning and construction phase. Knowledge gaps have been identified concerning the interface between the building construction and landscaping of the green roof. Quality assurance, in particular regarding handovers between different stakeholders, is highlighted. The need for a structured process including guidelines with check lists is particularly wanted by the industry.

4.1 Superstructure of vegetative (green) roof systems

With increasing urban densification and loss of urban green spaces, there is a growing interest and need for building based vegetative (green) roof systems, courtyard greenery above substructures such as parking garages and even roof top gardens for farming. More advanced vegetation systems, trees and particular ecosystem services are often prescribed.

Green roofs can be built for different reasons, with different target images and to stand for a specific function in relation to the building's users or the city at large. Delivery of the roof's functionality can be optimized by selecting the most suitable plants.

Green vegetation-covered surfaces contribute to a positive urban climate by increased humidity and lower temperatures. All vegetation-covered surfaces affect the urban water and heat balance in a profound way. When it comes to green roofs' impact on the city's temperature, it is primarily caused by the combined effect of evaporation and transpiration, usually termed evapotranspiration, but also reflection of incoming solar radiation can be significant. Evapotranspiration can be done directly through the interception of the falling rain which evaporates straight back to the atmosphere, by evaporation from the wet substrate surface after rain or by perspiration from plants that have taken up water through its roots. In certain climates, this temperature moderating effect can also influence the indoor thermal comfort and even reduce the need for air conditioning (Sikander, 2014).

Local handling of surface (rain) water discharge has been one of the main arguments for the use of green roofs in Sweden. Some vegetation-covered roofs have an ability to reduce runoff by more than 50 % on a yearly basis. They also have a significant impact on the peak flow runoff, which could reduce the risk of local flooding in the district and subsequent damages. The vegetative superstructure thickness is the most important factor for the reduction of storm water runoff but also the choice of plants may be of some importance in a similar manner to the urban environment.

If a vegetation is sought that has a maximum impact on the urban water balance and contributes significantly to lowering the temperature of the city, plants such as succulents are not suitable because they save water and have minimal transpiration. The plant's ability to cool must be weighed against its survival in a (heat-) stressed environment.

4.1.1 Green roof vegetation build-up

The traditional way of building up vegetation systems for green roofs and gardens is by installing a drainage layer to allow discharge of excess water and on top of this a substrate layer to anchor and support the plants with water, air and nutrients. Layers are often separated by a geotextile to maintain integrity of the materials and prevent particles from being washed out and blocking drainage paths.

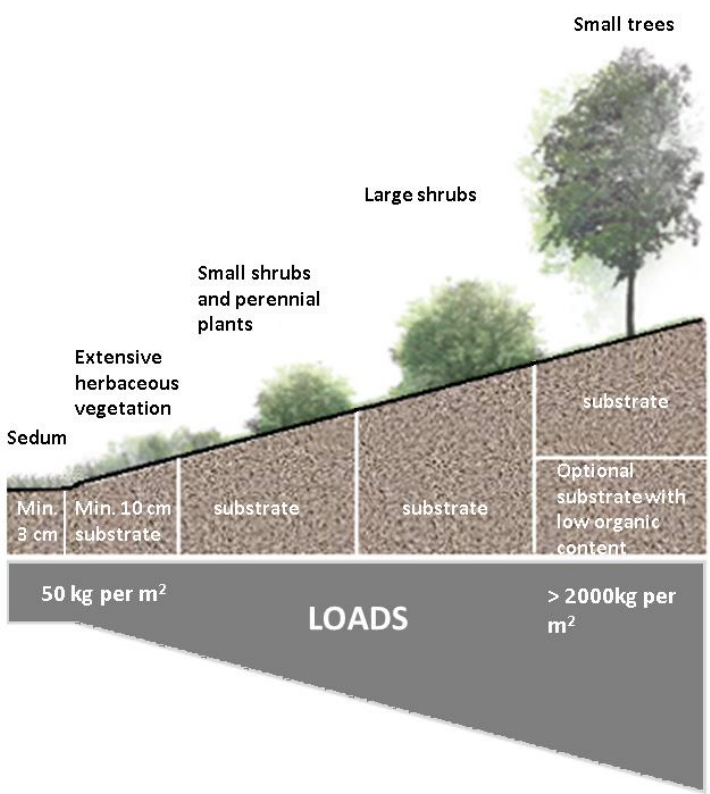

Fig. 3. Function of vegetation types relating to installation depths, giving different loads on the supporting concrete deck.

Substrate quality as well as the design and installation of different kinds of vegetation systems are important to consider when designing systems that are sustainable and resilient. Different kinds of substrates have varying air and water holding capacities; important parameters for plant selection but also on the water and heat balance as described above. The project handbook on green roof vegetative superstructures gives a description of feasible plant materials for different types of green roofs as well as examples of loads from substrate and vegetation. Figure 3 gives an indication of the increase in weight of a green roof system depending on substrate depth and selection of plant species.

Green roof systems are special in the sense that the vegetation contact with groundwater is broken and that the entire water supply rests on the incoming rain or irrigation. This makes the plant bed particularly vulnerable during extreme weather events such as drought.

Green roofs will always need waterproofing as runoff is expected. Often, some form of drainage to disperse excess water is needed during intense or extended rain. With more multifaceted green roofs and garden types, the number of choices, possibilities and systems' complexity increases. However, the key driving character for most variables related to design are the substrate depth and properties which have a direct influence on the demands put on the supporting structure.

Often the thickness and weight of the plant bed and superstructure can be an issue related to the capacity of the load bearing supporting structure and negotiations for slimmer superstructures are not uncommon in order to reduce costs. With limitations in the roof's carrying capacity, the vegetation has often limited space to grow. The total amount of water available is very limited making it even more important to use a substrate with a high water holding capacity. If not properly designed, the consequence could be a system that does not support the vegetation properly due to deficient water storage for long periods of drought and thereby increasing the demand for irrigation. Another consequence of inadequate design is oxygen deficiency during long periods of rain. This could be caused by too shallow planting beds combined with substrates with a high water holding capacity. Trees, shrubs and many perennials are very sensitive to lack of oxygen and the lower limit is considered to be around 10 percent by volume of air content (Handreck, 1989). In Figure 4, the correlation between soil depth, water distribution and air content is shown for a soil bed using a typical substrate.

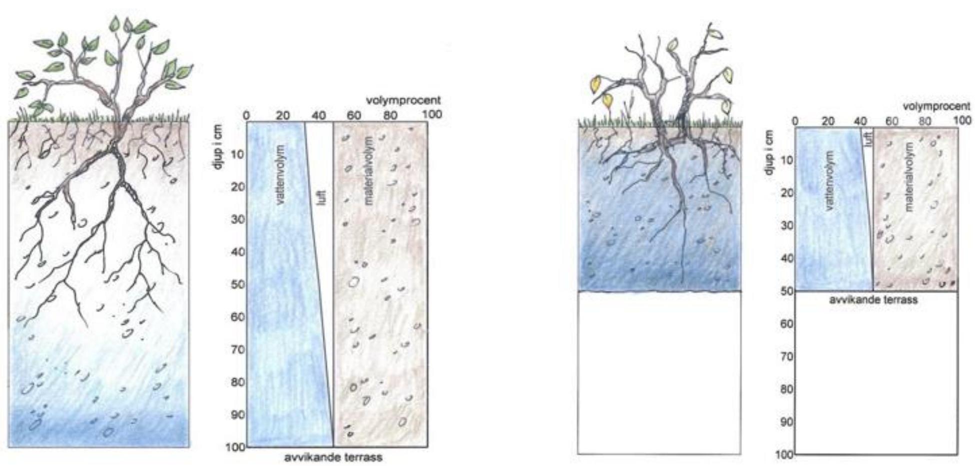

Fig. 4. Illustration of water distribution a thick (left) and shallow (right) soil bed using a typical substrate. In the shallow soil bed the air content is less than 10 % already at the surface, which is too low for most plants (Illustrator: Ingela Holm, Sweco).

4.1.2 Vegetative (green) roof loads

The roof's load capacity needs to be calculated both for the installation of a green roof during the construction phase as well as for the green roof built on the existing (or designed) roof. The roof should have the capacity to handle multiple loads such as wind and snow load. It should also be considered that people will be on the roof, for example, during maintenance of extensive green roofs or for recreation in intensive green roof gardens.

Both static and dynamic loads need to be taken into account, including loads arising during the construction and installation. Also, load calculations of green roofs always need to consider the weight of a water-saturated green roof, including water saturated substrate and other materials such as a water-saturated drainage layers.

In Table 1 preliminary examples of design loads from different vegetative (green) roof systems are presented along with requirement on root protection and waterproofing system. The total weight of all materials to be installed on the green roof should be taken into account. Trees and shrubs will be much heavier in the long term and there must be margins for this.

Table 1. Possible options for green roof build-up related to type of vegetative superstructures.

Vegetation type	Substrate depth (mm)	Substrate load (kg/m^2)	Vegetation load (kg/m^2)	Root protection	Waterproofing system
Sedum / moss	30-80	40-120	10	1)	Yes[2)]
Sedum / herbs	80-120	80-240	10	Mechanical / chemical	Yes[2)]
Lawn, field, perennials	120-350	120-700	5-15	Mechanical / chemical	Yes[3)]
Smaller bushes and perennials	300-600	300-1200	20-30	Mechanical / chemical	Yes[3)]
Larger bushes and smaller trees	600-1500	600-3000	40-60	Mechanical / chemical	Yes[4)]
Larger trees	1000-2000	1000-4000	150	Mechanical / chemical	Yes[4)]

1) For substrate depths up to 50 mm, root protection is not used according to Swedish praxis. The selected root protection could be a mechanical or chemical root protection. Examples of mechanical root protection are FPO membranes, thicker foil of polyethylene, mastic asphalt and more.
2) All normally occurring waterproofing systems for roofs. Bituminous and synthetic waterproofing systems are specified in the Swedish building regulation. Cloths should have a minimum thickness of 1.5 mm. If the products are not fully welded or glued to the concrete deck a wind load calculation must be performed for correct installment/fastening of the products.
3) Minimum one layer of bitumen sheet 5 mm (YEP 6500), alternatively two layers (YEP 2500) glued in oxidized bitumen or two layers YEP 3500 fully welded. If needed, a protective layer of concrete or mastic asphalt could be added. Alternatively 2x10 mm mastic asphalt on a layer of YAM 2000 could replace the previous solution.
4) Minimum one layer of bitumen sheet 5 mm (YEP 6500). If needed, a protective layer of concrete or mastic asphalt could be added.

Factors/elements that should be considered when estimating the roof structure's load bearing capacity:

- Gravel and/or concrete for edges and vegetation-free zones
- Snow loads
- Wind loads
- Plants and substrate
- Stored water in the substrate and the drainage layer (+ optional irrigation system)
- Additional structural elements for biodiversity habitat (dead wood, stones, etc.)
- Optional solar panels + anchoring system for panels
- Fall protections for safety of people visiting the roof
- People: maintenance personnel, private users of roof gardens, etc.

4.2 Waterproofing system, insulation and concrete deck

It is important to show certain basic conditions and requirements regarding design, materials and workmanship for the part of the green roof which is located under the green roof vegetative superstructure, that is, concrete, waterproofing systems and insulation. To this list is also included root protection, in some cases waterproofing protection layers, and structural details of various types. Although the project did not address the concrete load-bearing capacity, albeit giving advice on design loads of vegetative (green) roof systems, it focused on the concrete's surface structure and pretreatments that contribute to the best possible basis for materials such as waterproofing systems to be applied directly on top of the concrete decks. Often, this is a concrete surface primer combined with a waterproofing system. There are a variety of waterproofing systems and insulation materials on the market and the project handbook (Månsson, 2016), along with referenced documents, provide advice for selection of products / systems. Detailed sketches of critical details are also provided as well as requirement levels for materials and checklists for installation and leak testing as well as recommendations on how to protect the waterproofing layer during the construction process.

The build-up of a vegetative (green) roof system should also be seen from an energy perspective in the light of our Swedish climate. Insulation properties, the cooling effect from evapotranspiration, etc. should be taken into account. When installing, for example, an inverted roof where the insulation will be exposed to moisture, it is important that the insulation will not be degraded and loose insulation capacity. It is also important to ensure proper drainage to remove excess water.

Waterproofing layers in vegetative (green) roof systems must be resistant to root penetration, mechanical and chemical degradation, loads and ageing effects. Selection of waterproofing layer/system depends on many factors including type of roof, slope, loads (both during installation and in service) and plant/substrate selection. There are, for instance, plants with non-aggressive root systems, making root protection redundant, given that new species are not introduced in the future.

Regarding the concrete, there are, apart from the concrete structure/roof itself, other concrete details and fittings to take into account. As mentioned earlier, there are protection layers made of concrete for waterproofing systems, along with different mortars and concrete used for building up and supporting roof edge barriers. Topics that could be considered and treated concern, for instance, leaching carbonates that may cause sintering in dewatering and drainage facilities. Hence, the use of calcareous aggregates in dewatering, drainage or protection layers is not recommended.

Before applying a waterproofing system on the concrete surface, the surface quality must be assured for safeguarding proper adhesion. Given that the adhesion to concrete cannot surpass the concrete surface tensile strength, pretreatment work including cleaning of the surface is necessary. Any contaminant must be removed for a primer product to work properly and penetrate the concrete. Again, the concrete surface must be strong enough for the waterproofing layer in order to avoid adhesion loss due to tensions that may arise, thus detaching the layer from the concrete. It is recommended that the concrete surface tensile strength is determined on site before applying the waterproofing layer. Other important factors to consider are surface temperature and moisture conditions as these can highly influence for instance curing time of a thermoset material.

The concrete surface is usually sealed with a primer in order to increase surface adhesion before any waterproofing system is installed. The primer treatment permeates into the concrete and will give certain moisture-resistant and dust-binding effects. It is important to establish whether the primer and waterproofing system are compatible and form a functioning system in combination or if there are adverse effect caused by for instance chemical reactions. Primer products for protective treatment of concrete could be epoxy, urethane primer and acrylate based primers.

There are a number of different types of waterproofing systems available for green roofs on concrete deck. They are supplied in different forms such as rolls, cloths or liquid dispersed systems. The properties of the waterproofing system must be selected taking into account both the final stage when the green superstructure is in place and thus considering the vegetative superstructure weight caused by substrate material density, substrate depth and the subsequent hygrothermal loads, see examples in Table 1. Also important is the construction stage, before the layer is covered, when work will be performed on the roof and construction traffic is expected. In addition, the membrane/layer must also resist pressures and strains from movements that could occur in the structure and from the environment given by the superstructure.

The following listed parameters can affect the waterproofing system's performance over time, and influence the green roof's protection against water penetration into the construction.

- Water tightness of waterproofing and joints, penetrations and drainage wells
- Water resistance after movements in the concrete deck structure
- Water tightness of connections, e.g. at eaves and wall
- Resistance to water vapor
- Elasticity at low temperatures or ice-stress tolerance
- Puncture resistance
- Tensile strength of joints
- Root resistance
- Frost resistance
- Ageing resistance
- Resistance to UV radiation for waterproofing that will be exposed to sunlight
- Resistance to fire
- Resistance to wind load
- Adhesion to the concrete substrate

5. Conclusions

When designing a green roof, it is important to know exactly what the intended use is meant to be for the roof, in terms of aesthetic appearance or ecosystem services functionality. Roof design may vary significantly depending on the desired functions. Given that the vegetation will have great significance on the choice and requirements of all underlying layers such as plant bed, drainage, waterproofing and concrete deck, the design and construction will be based on the vegetative superstructure and plant-bed build-up. Consequently, the underlying structure should be designed and constructed from this viewpoint. The project results (guideline and handbooks) emphasize that high requirement should be placed both on the concrete structure as well as the vegetative superstructure. The handbooks provide more in depth knowledge for the client.

It is important to include all stakeholders early in the process and to clarify important mile stones in the planning and construction phase. The project handbooks and guideline will greatly reduce knowledge gaps that have been identified in the green roof construction process. Quality assurance has been addressed by the guideline, handbooks and proposed check lists.

6. Acknowledgements

The project is largely financed by Sweden's Innovation Agency, Vinnova, and also co-financed by the project partners. The authors would like to thank all project participants and reference groups that contributed with their knowledge and expertise in the project.

References

Brenneisen, S. (2006). *Space for Urban Wildlife: Designing Green Roofs as Habitats in Switzerland*. Urban Habitats, (4), pp. 27-36.

Edwards, Y., Emilsson, T., Malmberg, J. and Pettersson Skog, A. (2014). *Quality-Assured Solutions for Green Roof Gardens on Concrete Decks with Zero Tolerance for Leaks*. The Sustainable City IX (2 Volume Set).

FLL Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V. (2008). *FLL Richtlinie für die Planung, Ausführung und Pflege von Dachbegrünungen – Dachbegrünungsrichtlinie*. Bonn: Germany.

Handreck, K. A. and Black, N. D. (1989). *Growing Media for Ornamental Plants and Turf*. Rev. ed. Kensington: New South Wales Univ. Press.

Li, Y., Babcock Jr., R.W. (2014). *Green roof hydrologic performance and modeling: A review*. Water Science and Technology, 69 (4), pp. 727-738, University of Hawaii at Manoa, Honolulu: United States.

Månsson, H. (2016). *Handbok - Betong, Isolering och Tätskikt för Gröna Tak/Anläggningar på Betongbjälklag*. Vinnova, Sweden.

Pettersson Skog, A., Malmberg, J., Emilsson, T., Jägerhök, T. and Capener, C.-M. (2016). *Handbok – Överbyggnad för Gröna Tak*. Vinnova, Sweden.

Sikander, E. and Capener, C.-M. (2014). *Gröna Klimatskal - Fuktförhållanden, Energianvändning och Erfarenheter*. SP Rapport 2014:53, Borås: Sweden.

Takebayashi, H. and Moriyama, M. (2007). *Surface Heat Budget on Green Roof and High Reflection Roof for Mitigation of Urban Heat Island*. Building and Environment, (42), pp. 2971–2979.