

Climate Resilience and Circularity in Construction assignments

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Innovations in soft soils and building materials

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1 Supporting investments in area development with scientific insight

This report is the result of the Work done in work package 4 'Construction assignments' in the Adaptive Circular City project, with contributions of Deltares, ECN, Alterra and TNO.

1.1 Context: construction assignments

The work package 'Construction assignments' aims at the inclusion of climate resilience and resource efficiency in work on constructions (buildings and infrastructures). This work can either be a new construction, or renovation and maintenance of buildings, roads and squares.

1.1.1 Increased Resource efficiency

Resource efficiency is related to the material, water and energy flows in the city. The construction assignment (renovation and construction) offers an investment point where the resource efficiency of these flows can be increased; both by their deployment for the production of building material, as the efficiency of these flows during the use of roads, squares and buildings. The mineral building materials (paving, facade and roof) are dominant in the resource use of most construction tenders, and therefore crucial in increasing the resource efficiency of construction. The building envelope (façade and roof) is also a great influence on the energy efficiency of a building.

Circular economy offers various approaches to increase resource-efficiency; from closing cycles by more use of waste and other material flows in the city, and bio-based building to life extension. An example of a material chain in which circular economy plays a part is the concrete chain. Construction and demolition waste and other waste may, possibly after processing, be used in concrete. When concrete is made from secondary materials and recycled concrete granulate is again in concrete applied, questions arise about the next life cycles with respect to emissions and bind the carrying capacity of the soil substances, and the number of life cycles continue to be to continue to meet emission requirements. If one could predict how materials continue to behave in repetitive reuse, a better picture of the potential of these materials for a circular economy can be created.

1.1.2 Climate resilience

Global climate change leads to more tropical summer days and more days with extreme rainfall. Cities concentrate the population and economic capital and are therefore vulnerable to climate change. Globally, the most growth of cities takes place in delta regions, where soft ground and subsidence affect the construction statement. Investments in the built environment that are done now (such as construction or renovation) impact buildings and infrastructures for the next 50 years or more, as most building assets have often long lifetimes. Therefore it is important to consider climate resilience in today's investments in the built environment.

Global climate change leads to more summer and tropical days and to more days with extreme rainfall. Climate-proofing the city also has to do with preventing nuisance by heat and heavy rainfall. The paved area of the city, located in facades, roofs and paving (and relationship to the existing green and blue) has a major influence on the climate resilience. Nuisance caused by heat can be restricted for example by more shade, more albedo (reflection from light surfaces) or cooling through evaporation. At times of renovation and construction can be explored which products, texture and architecture of the paved area of the city lead to a more climate-resilient city

1.1.3 Soft foundation soils

Soft foundation soils pose numerous technical problems pertaining on the sustainability of constructions. Examples are early wear and tear of infrastructure, both on and under the surface, due to differential settlement. Also shallow founded buildings fall victim to poor bearing strengths and behave poorly in comparison to constructions in areas with higher bearing capacities, such as sandy subsoils. Traditional building methods have led to short life spans in general and high maintenance costs. In recent years many tools and methods have been developed that improve the life span of constructions. Management tools have been developed that anticipate the maintenance cycles and help in choosing the most effective and economic methods in a particular situation, reckoning with the demands on the constructions and the demands posed by the subsoil. The increased lifespans will lead to a reduction in the use of material resources.

1.2 Used approach

Climate-proof and resource efficient building requires new construction solutions and collaboration between governments, organizations in the construction sector and knowledge institutions. This work package is the social impact of various building solutions (including emerging technologies) over the life cycle transparent, as input for a sound business case.

This work package is organized against three different conceptual levels that differ in scale, stakeholders, and investment related questions:

- The first level targets difficult soil conditions and its relevance for city planning and design for new construction assignments and for large redevelopments. Due to a growing population, cities are being developed on land with poor soil condition. Improper design and planning results in all kinds of problems that are costly, poor in resource efficiency, and vulnerable for climate change. Chapter 2 describes these issues and gives an inventory of technologies and assessment models that can be used.
- The next level targets the main material flow for buildings and infrastructures, being mineral building materials. Besides that fact that this is the largest material flow for the construction of buildings and infrastructures (both in resource need as well in waste), mineral building materials are also dominant in the 'hard surface' in cities (that is relevant for potential impact of heat and rainfall). The building envelope (façade and roof) is also a great influence on the energy efficiency of a building. Chapter 3 describes circular economy for mineral building materials, and what technologies and methods are available to design products that contribute to climate resilient cities.
- The last level targets roofs. Roofs are a building component that impact the building itself as well as the area. Chapter 4 describes the differentiating roof top solutions, what the impact is and how tools to assess impacts can be used for decision making on roof top investments.

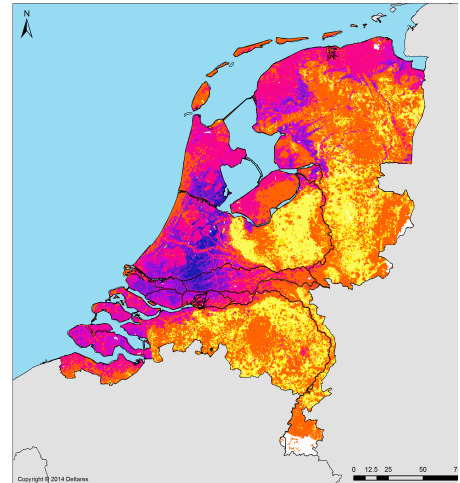
The last chapter, chapter 5, describes 'cases' where investments in buildings and infrastructure are made, or have to be made, and where the knowledge that is combined in this contribute may be useful for decision making.

2 Optimizing Constructions for the Subsurface

2.1 Requirements/ KPI's/ societal impacts

In the Netherlands the preparation of building sites and roads is normally performed by raising the site level with additional sand and preloading with temporary extra height. The aim of building site preparation is to create a subsurface layer with the right bearing capacity and drainage level to enable temporary road works during the construction phase of a project development.

High quality of the preparation of building sites and roads is a necessity in the western part of the Netherlands where the soil consists of vast layers of soft clay and peat. In the regions where these soft soils are found, land subsidence is a serious problem, also related to the lowering of the groundwater table in polders. Also loading of the surface can result in on-going settlements (*Figure 2.1*).



Due to the growing need for housing development around the big cities, land reclamation in soft soil regions has been expanding (*Figure 2.2*). However, because of the difficult soil conditions and the lack of proper design tools in the past the site preparation was not optimal. The consequence of the lack of quality in the design and preparation was the occurrence of large subsidence and settlements in the city districts that were developed until around 1990. Typical phenomena in those areas are:

- Bumpy road tracks and pavements,
- differential settlements between streets and buildings on pile foundations,
- damage to buildings and road infrastructure,
- utility connections at risk (sewerage, water and gas pipes)
- small depth of dewatering and drainage and
- increased risk of storm water flooding during extreme weather.

Figure 2.1 Settlement sensitivity to surface surcharge

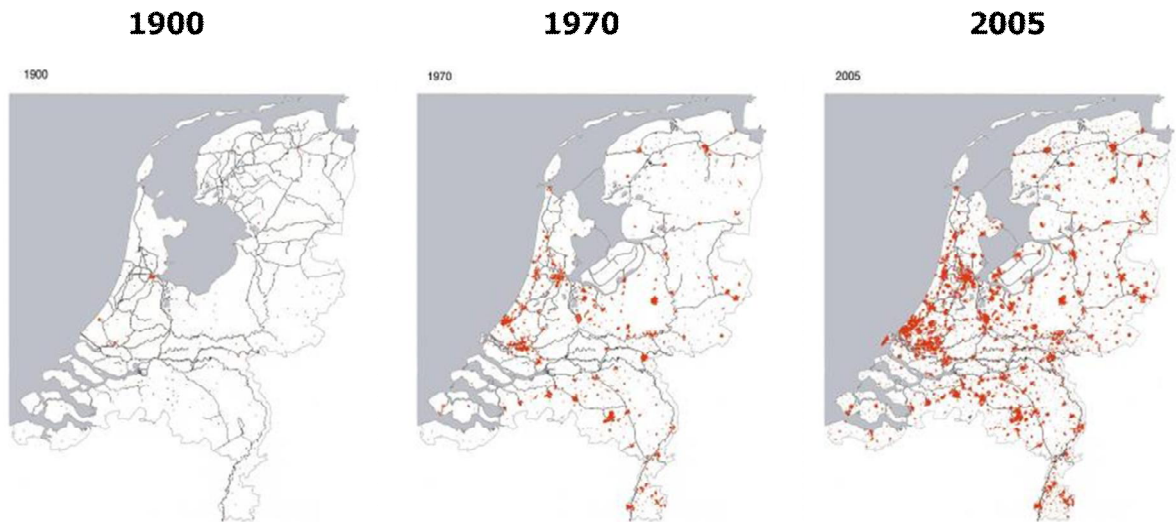


Figure 2.2 Spatial expansion of urban land use in the Netherlands in the last century (source: PBL, CBS)

In 2014 Deltares studied the current problems related to subsidence in soft soil regions [Deltares, 2014, Resultaten vooronderzoek onderhoudsstrategie infrastructuur bij bodemdaling 1209950-000-GEO-0007, November 2014]. By interviewing managers of municipal public works departments the following inventory of damage to urban infrastructure was identified in relation to soft soil conditions:

- maintenance by levelling up of roads in existing urban area is complex and costly (because of spatial factors, public interests in the neighbourhood, reconstruction of utility pipes and cables);
- maintenance costs for roads and sewer systems are large where soft soil is present (up to 50% higher in interviewed cities in soft soil regions, whereas nationally averaged 10% higher expenses are found);
- maintenance costs are rising due to climate change: storm water flooding in streets occurs more often; cost increase unknown;
- low groundwater levels during periods with extreme meteorological drought cause damage (stronger land subsidence, damage to foundations) and this probably is most important cost aspect in existing urban areas;
- high groundwater levels are mainly caused by construction errors in building site preparation and this probably is the most important cost aspect in newly developed urban areas (higher maintenance frequency).

A problematic burden for the municipal departments of public works is the rising cost of maintenance in the indicated soft soil regions due to frequently needed levelling up of roads and transitional structures near waterway crossings and sewerage systems. Of course, it is very inefficient to perform repair works frequently during the maintenance phase due to insufficiently designed and prepared building sites and roads. Maintenance by levelling up will be followed again by restart of a new subsidence process, and thus uncontrolled repairs will become a vicious circle.



Figure 2.3 Some views of subsidence effects in soft soil regions in the Netherlands

With latest research results on compaction behaviour of soft soils, recently developed design tools, new construction methods and satellite monitoring techniques, modern tools are available to create a breakthrough. Therefore a more robust and durable arrangement of civil works in the context of urban development is within reach.

The overall objective of the project Adaptive Circular Cities is to contribute to a breakthrough in cross sectorial investment decisions regarding urban concepts that take into account climate resilience, mitigation and resource efficiency.

2.1.1 Demands and KPI's to optimize building on soft soils

Key performance indicators (KPI's) for subsurface solutions should focus on these three topics. The aspects can be further divided in impact categories (*Table 2.1*). To assess these impact categories, various indicators can be defined. Each indicator has different characteristics, e.g. regarding relevance, data availability, reliability and familiarity. It is therefore important to discuss which indicators are best suited for which use case.

The following impact categories and indicators can be related to the proper design of the preparation of building sites and roads. By prolonging the maintenance frequency of infrastructure in soft soil regions resources like building materials will be used more efficiently and thus the resource efficiency will be improved. Energy use and emission of greenhouse gasses will go down subsequently. When roads and sewer systems are less frequently replaced the amount of waste will be diminished. Due to climate proof design and less differential settlements, sewer system will perform better and storm water flooding will be decreased.

Table 2.1 KPIs for subsurface aspects in adaptive circular cities

Impact area	Impact category	Indicator
Mitigation	Global warming	Greenhouse gas emissions (kg CO₂-eq.)
Adaptation	Water nuisance/flooding	- Water retention (m³; % of local retention needed) - Infiltration (% of unpaved surface; m³ of infiltrated water; % of infiltration needed) € saved
Resource efficiency	Energy	Energy use (MJ final energy; €)
	Materials	- Materials used (kg) - Share of recycled/bio-based materials (% of consumption) - Life time (years; extended life time) - Waste (kg/capita)

2.1.2 Current score on the selected KPI's

The most interesting indicators when maintenance of roads is studied are related to the durability aspect, concerning CO₂-emissions, energy use and material recycling and life time.

Recently studies were performed for the construction of road widening projects for highways in the Netherlands. For instance the available design code MRoad is dedicated to the assessment of several design aspects for road construction, including durability. The project dimensions, pavement design, traffic properties and soil conditions are the input for the assessment. The program MRoad is able to calculate the residual settlements to evaluate the maintenance cycle after construction phase.

To compare the costs of several solutions in maintenance strategies a code Balans was developed by Deltares around 2010 during the Delft Cluster program especially for municipal maintenance departments. However, due to the specific soil mechanical character and required level of technical know-how the use of the instrument is stagnating. A new showcase might help introducing this instrument and showing the opportunities.

But other design codes are specifically arranged to check environmental aspects, like Urban Strategy by TNO or DuBoCalc for the Dutch Road Authorities by SenterNovem. The latter program is designed to perform a life cycle analysis LCA.

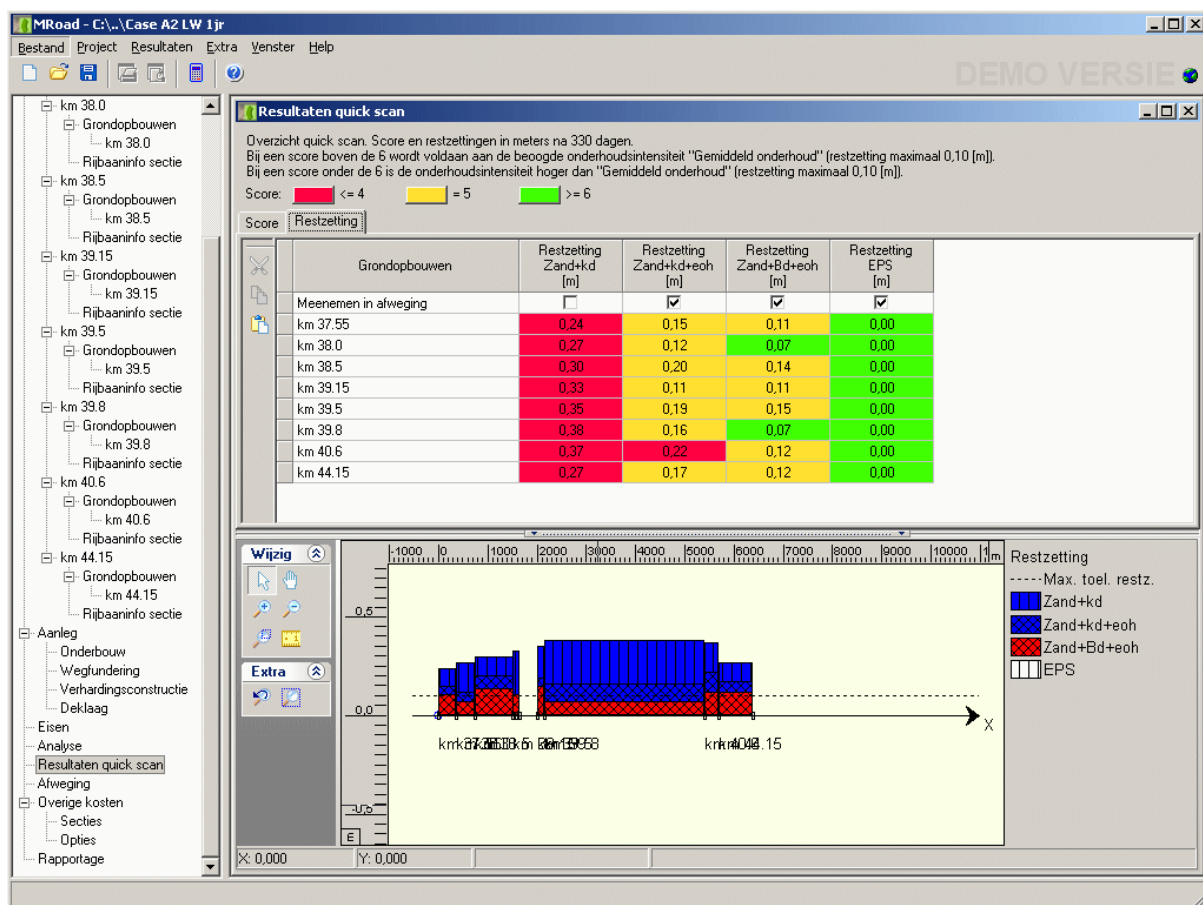


Figure 2.4 Comparison of assessment results of several road maintenance methods with MRoad

Table 2.2 Assessment methods for road maintenance

Assessment aspect	MRoad	Balans	CROW KMW	CROW AMW	TNO Urban Strategy	DuBo-Calc
Design quality						
Costs						
Construction time						
Traffic disruption						
Nuisance to neighborhood						
Durability						

These design codes are quite new and are not yet in use for urban planning of new housing development claims and the assessment of local roads. The TO2 program might give a great opportunity to attract municipal public works offices to experiment with these tools.

2.1.3 Example of scoring traditional versus innovative methods

In the study of practical tests for maintenance strategies in the village Kamerik (Deltares, 2015, report 1210948-000-GEO-0002-r-Proefvakken Overzicht Kamerik_final_draft.pdf) 5 alternative road constructions were compared to traditional repair with leveling up by an extra sand body. The study showed that in an economical assessment for maintenance of local village roads most alternative solutions are not cost effective. However, to gain insight in durability aspects the environmental costs should be taken in and need to be evaluated.

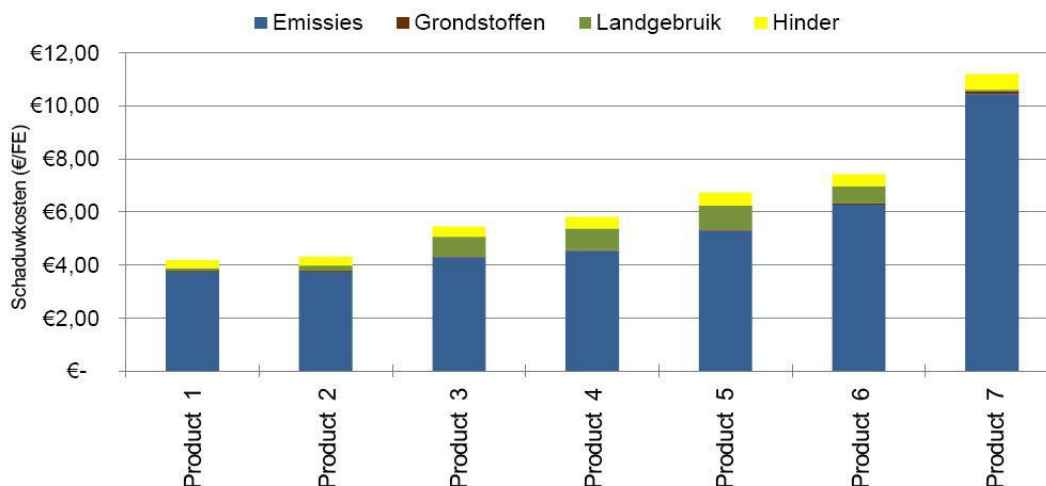


Figure 2.5 Comparison of assessment results of several road maintenance methods

When the Life Cycle Analysis is taken into consideration, the balance of the assessment shifts a bit in favor of construction methods with the lightweight material Yali Bims.

Table 2.3 Results of an LCA Assessment for road maintenance methods in Kamerik

materiaal	LCA schaduwkosten [EUR]										
	YaliBims	zand	schuim- beton	EPS nieuw	EPS 100% recycling	EPS 100% recycling menggran	paalmatras menggran	paalmatras zand	schuim- glas	versterkte baggerspecie	
Ontgraven											
Frezen asfalt	€ 2.755	€ 2.755	€ 2.755	€ 2.755	€ 2.755	€ 2.755	€ 2.755	€ 2.755	€ 2.755	€ 2.755	
Ontgraven slakken	€ 9.755	€ 9.755	€ 9.755	€ 11.667	€ 11.667	€ 11.667	€ 14.536	€ 14.536	€ 9.755	€ 9.755	
Ontgraven zand	€ -	€ -	€ -	€ 2.121	€ 2.121	€ 2.121	€ -	€ -	€ -	€ -	
Verharding											
Betonstraatstenen / Stoeptegels	€ 34.842	€ 34.842	€ 34.842	€ 34.842	€ 34.842	€ 34.842	€ 34.842	€ 34.842	€ 34.842	€ 34.842	
Fundering											
Straatzand	€ 2.032	€ 2.032	€ 2.032	€ 2.032	€ 2.032	€ 2.032	€ 2.032	€ 2.032	€ 2.032	€ 2.032	
Menggranulaat	€ 9.500	€ 9.500	€ 9.500	€ -	€ -	€ 24.570	€ 38.144	€ 9.500	€ 9.500	€ 9.500	
Ophoging											
Yalibims	€ 15.022	€ -	€ -	€ 11.408	€ 11.408	€ -	€ -	€ -	€ -	€ -	
Zand voor zandbed	€ -	€ 26.178	€ -	€ -	€ -	€ -	€ 10.514	€ 33.688	€ -	€ -	
Schuimbeton	€ -	€ -	€ 63.112	€ -	€ -	€ -	€ -	€ -	€ -	€ -	
EPS nieuw	€ -	€ -	€ -	€ 47.507	€ -	€ -	€ -	€ -	€ -	€ -	
EPS 100% recycling	€ -	€ -	€ -	€ -	€ 9.522	€ 9.522	€ -	€ -	€ -	€ -	
Houten palen 0,12 m voet, duurzaam beheerd bos L=8,4 m	€ -	€ -	€ -	€ -	€ -	€ -	€ 13.393	€ 13.393	€ -	€ -	
Paalkoppen beton 0,40 m diam H=0,25 m	€ -	€ -	€ -	€ -	€ -	€ -	€ 12.553	€ 12.553	€ -	€ -	
Geogrids	€ -	€ -	€ -	€ -	€ -	€ -	#N/A	#N/A	€ -	€ -	
Schuimglas	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	#N/A	€ -	
Versterkte baggerspecie	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ 69.174	
Onderhoud											
Herstraten t=25 jr	€ 4.279	€ 4.279	€ 4.279	€ 2.140	€ 2.140	€ 4.279	€ -	€ -	€ 4.279	€ 4.279	
Plaatselijk herstraten t=12,5 jr	€ 428	€ 1.070	€ 428	€ 428	€ 428	€ 428	€ 214	€ 214	€ 428	€ 428	
Plaatselijk herstraten t=37,5 jr	€ 428	€ 1.070	€ 428	€ 428	€ 428	€ 428	€ 856	€ 856	€ 428	€ 428	
TOTAAL	incl #N/A excl #N/A	€ 79.042 € 91.482	€ 127.132	€ 115.327	€ 77.342	€ 92.644	#N/A € 129.838	#N/A € 124.369	#N/A € 64.020	€ 133.194	
toev Bims	100%	116%	161%	146%	98%	117%	#N/A	#N/A	#N/A	169%	

2.1.4 Side effects of innovative methods

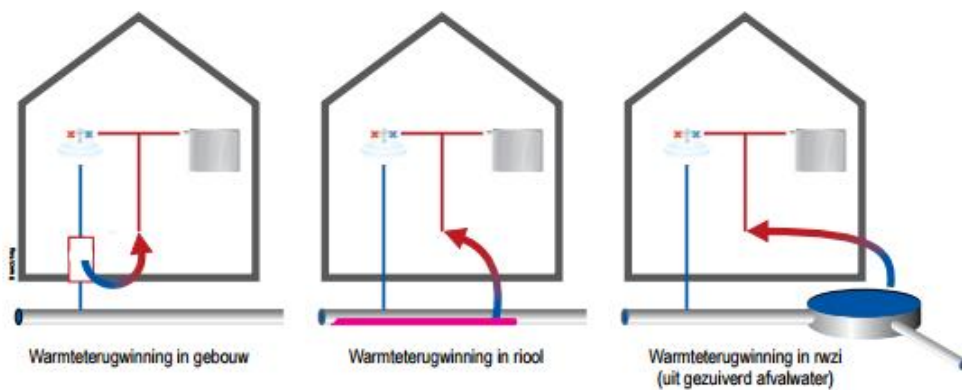
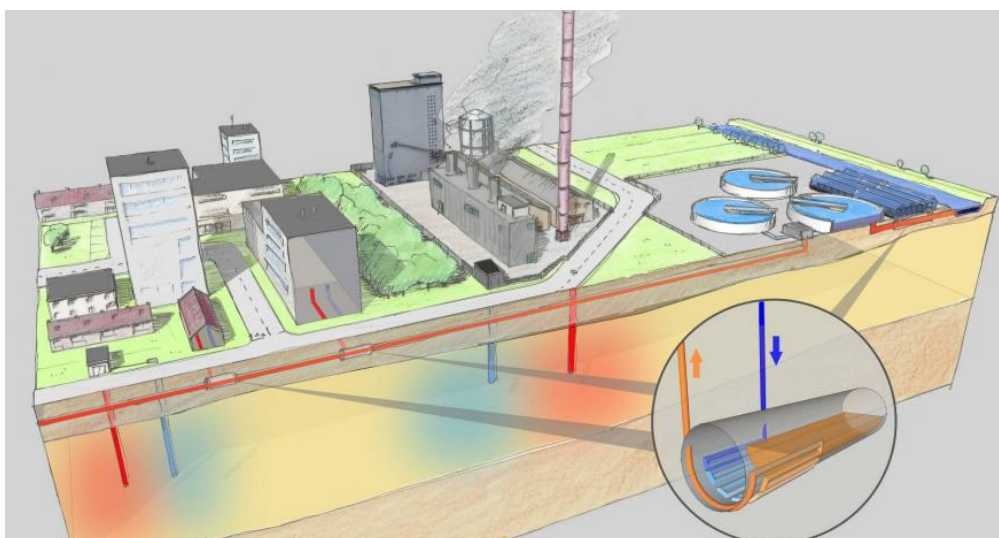
Nevertheless, the result of this study for Kamerik is considered to be a very odd outcome because the Yali Bims material is mined in and transported from Greece and expected emissions would therefore be relatively high; certainly if this method is compared with construction types that use recycled material like piled mattress systems. Therefore, our conclusion is that at present methods are available to study LCA assessment but the input factors are probably deviant and need to be verified urgently before practical application of the LCA assessment for road maintenance can deliver reliable results. The national road construction contractors and all municipal road departments in soft soil regions would benefit from improvement of the current design instruments. Currently Deltares is involved in the design and evaluation of test sites for road maintenance in Kamerik. The monitoring of the test sites is expected to deliver excellent data by which the verification of the outcome of assessments can be calibrated.

There are no negative aspects expected in the application of the new methods if applied appropriately. For instance, the use of Styrofoam elements should be avoided if it hampers a previously existing natural flow of water through the soil. However as mentioned above, the use of Bims poses an environmental deterioration, not only through the long transport routes, but also by destroying the landscape in the mining area.

2.2 Technology description: readily available Breakthrough technologies supporting circular and climate-proof objectives

2.2.1 Multifunctional solutions:

The creativity in the sector is aimed at finding new solutions for subsurface water and energy storage in the public domain of the city area. At this moment new initiatives for combined use of transport infrastructure and energy recycling are in development, like energy recycling from sewerage systems. However, these initiatives are already experiencing a great leap forward. Specialized consultancy firms in this area like Tauw have the knowhow to deliver advice on the application of these new systems.



Individuele en collectieve warmtewisselaars



Figure 2.6 Recycling of heat from sewer systems [Reference:
http://www.joostdevree.nl/bouwkunde2/jpgr/riothermie_2_kregting_www_tauw.nl.pdf]

Also subsurface storage of rain water or infiltration of storm water through pavements will give options for reuse of water, with cost savings resulting from a more efficient design of the sewer system. These options are implemented in urban infrastructure with a growing rate. However, this is a readily developed method. Nevertheless, for the TO2 it can be worthwhile to study how new housing developments can benefit from storm water storage solutions to enhance the durability factor in the plan. On the other hand, the application of infiltration of storm water in the subsurface in soft soil areas is not very likely to be beneficial, since the permeability of the soil is very low and the groundwater level is rather high. Research into the successful implementation of these kinds of hydrological measures will be studied in work package 2 of TO2.



2.2.2 Pile matrass: a recent breakthrough

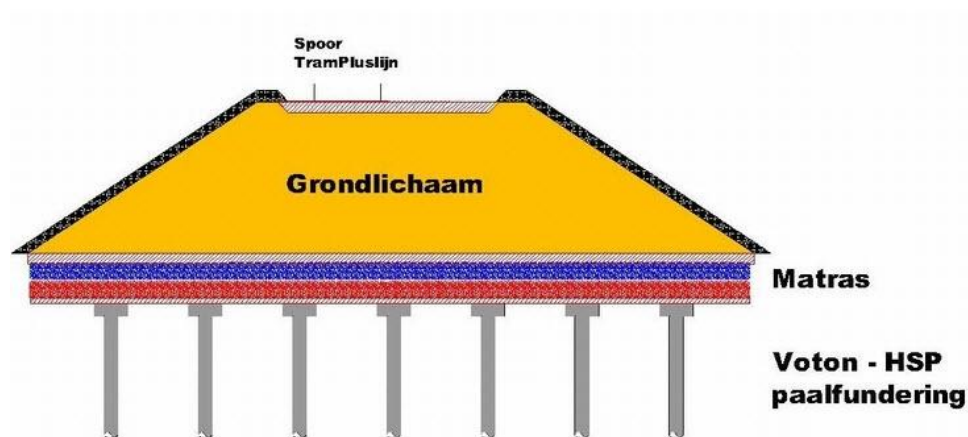


Figure 2.7 Example of a piled matrass construction [Voorbij Funderingstechniek]

Going back from hydrological options to road reconstruction, it is interesting to look at the benefits of new solutions for the construction of roads that are currently under study at Deltares. Especially the piled matrass is a recently developed construction method that offers great opportunities for road construction in soft soil regions, in the Netherlands and abroad. At present the applications are for the largest part in provincial roads and highways. The reason is that those roads are constructed at a high level and the effect of high groundwater on piled matrass roads is not yet studied. Also it is unknown whether the presence of a sewer pipe or utility services in the construction might have an adverse effect on the construction, e.g. during maintenance. A combination of piled matrass with water storage in the granular fill would be very interesting. If the groundwater level is allowed to be high without adverse influence on the bearing capacity or strength of the construction, new applications for durable roads in cities on soft soil would be possible. A strong point of these constructions is that the construction time is relatively short. Therefore it

is interesting to use this type of construction for the first roads during the first phases to open a soft soil region for construction works.

2.3 Considerations regarding investment

The most preferred situation would be by creating a living lab to test new road construction methods and maintenance strategies in a municipality that is confronted with mid-term large investments on new housing development in a soft soil region. In that respect the TO2 initiative is very fortunate to have found cooperative municipalities that are facing those challenges and are interested in durable solutions. The growing city of Almere embraces a number of basic rules, the “Almere Principles” for a sustainable city development that beautifully relate with the TO2 goals, exemplified by some of those principles: aiming at lasting combinations of the urban and natural fabric, anticipating on change by adaptability in plans, improving on innovative processes, designing healthy systems (<https://english.almere.nl/the-city-of-almere/almere-principles/>)

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3 Mineral Building materials

3.1 Requirements/ KPI's/ societal impacts

For both buildings and infrastructure, demands are often translated into (technical) performance demands and the prevailing legislation describes the minimal requirements.

the technical properties are also addressed by the European Construction Products Regulation (CPR, EU/305/2011) that defines seven Basic Requirements for construction products: (1) Mechanical resistance and stability, (2) Safety in case of fire, (3) Hygiene, health and the environment, (4) Safety and accessibility in use, (5) Protection against noise, (6) Energy economy and heat retention and (7) Sustainable use of natural resources. The regulations states that construction works as a whole and in their separate parts must be fit for their intended use, taking into account in particular the health and safety of persons involved throughout the life cycle of the works. Subject to normal maintenance, construction works must satisfy these basic requirements for construction works for an economically reasonable working life. Once harmonized standards for testing of the basic requirements are finalized, producers need to declare the product performance using the CE declaration of performance.

This project has a focus on circularity and climate resilience. There are two options to integrate these additional demands in the set of requirements: 1) obligatory – ‘need to have’s’ and 2) voluntary – ‘nice to have’s’. It is realized that there is a difference between climate mitigation and climate adaptation. The goals to mitigate climate change are global discussions (e.g. CO2 reduction, transition to renewable energy systems etc.) and call for sometimes other solutions than the objectives with regard to climate adaptation in cities. In the latter case, alternative design, use of materials and local solutions are applied to improve the local climate (more cooling, improved water management) and decrease local negative impacts of climate change (e.g. flooding, heat stress). As an example, the carbon footprint of building materials is a relevant indicator for assessment of climate change impacts but this indicator is not useful to assess performance within the adaptive circular cities concept (because the carbon footprint does not directly improve the local climate in the city). Consequently, potential other indicators are relevant for adaptive circular cities than the sustainability indicators that are currently used.

The term “circularity” is widely used nowadays and derived from the definition of the circular economy: A circular economy is one that is restorative and regenerative by design, and which aims to keep products, components and materials at their highest utility and value at all times, distinguishing between technical and biological cycles (Ellen MacArthur Foundation). The concept is given schematically in Figure 3.1. A distinction is made between biological materials and technical materials. The options with shorter loops (e.g. maintenance) are preferred over options with bigger loops (e.g. recycle). The aim of the circular economy concept is to keep products and materials in the value chain for as long as possible at the highest level of utility. Waste that cannot be avoided needs to be managed in the most sustainable way. It is noted that Figure X does not contain arrows after energy recovery (or landfill) back to the Service provider or Product/Parts manufacturer. It is already quite common that materials after energy recovery (e.g. coal fly ash, municipal solid waste incinerator bottom ash) are re-used as/in construction products. On the longer term, materials might also be brought back into the material loop by landfill mining.

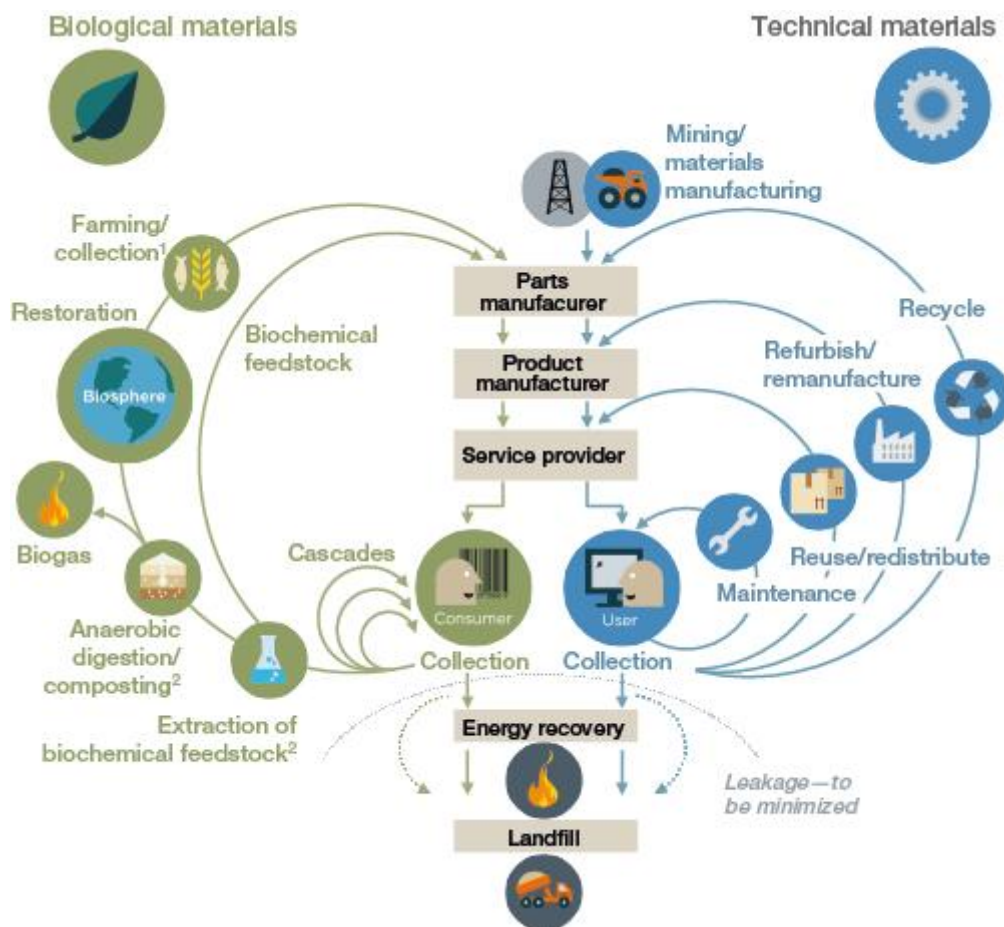


Figure 3.1 Material stages and options to keep them in the value chain in view of the circular economy concept (Ellen MacArthur Foundation circular economy team drawing from Braungart & McDonough and Cradle to Cradle).

Based on the principles of circular economy, developments have started to create “circular” materials. In principle, these circular materials should stay in the value chain without substantial losses. However, a clear definition of circular materials is currently lacking. For example, it can be questioned if a material can be regarded “circular” if it can be re-used for two times. Most probably, the opinion towards circularity does also depend on the life cycle time of materials. Plastic bottles have a relatively short life cycle of less than one year, while a building material would have a life cycle of more than 50 years.

3.1.1 Demands and KPI's for Circularity

For new buildings it is obligated in the Dutch building regulations to calculate the greenhouse gas emissions and resource use related to material use for the building over its life cycle. These two KPI's are thus obligated for new buildings. In 2018, maximum requirements will be set for building-related greenhouse gas emissions and resource uses. Circular building practices do have the potential to result in both lower CO₂ emissions and resource consumptions. By assessing and comparing these two obligated KPI's for circular building options, building solutions with the best performance can be selected.

In addition, Circularity in the building sector can be stimulated by obligated requirements of authorities in the permitting procedure and by voluntary green deals where private companies and governmental bodies work together to achieve circularity (for example green deal Cirkelstad). In these green deals, the ambition level can be set higher compared to the current building regulations. KPI's for sustainability or circularity can support both initiatives to select effective measures/ regulations and to monitor the impact of additional requirements of green deals.

For infrastructure, sustainability (or other societal benefits) is more often rewarded in green (public) procurement. The most economically advantageous tender (MEAT) criterion enables the contracting authority to take account of criteria that reflect qualitative, technical and sustainable aspects of the tender submission as well as price when reaching an award decision. In the Netherlands, the software tool Dubocalc is often obligated to be used to specify the 'MKI/ MilieuKosten Indicator' (environmental cost indicator) which is a weighted score of environmental impact. Circular building options have the potential to lower the MKI and, therefore, MKI is one of the relevant KPI's for the use of mineral building materials in infrastructure projects.

With respect to circularity, economics are driving the amount of circularity, such as costs of primary resources and logistics, costs of material separation and costs for upgrading of secondary materials and economy of scale. Life cycle costs are thus an additional KPI, that is also supportive to see whether there is a sound business case for circularity as is, or whether new business models are needed. For new business models it may be supportive to assess the societal costs and benefits of a circular building solution. For example if one can predict how many jobs there are created in a region as a result of circular economy, there may be possibilities for the local authorities to stimulate those circular building options that will generate enough economy of scale for a sound business case.

The building sector does already make use of secondary material flows from other sectors. For example gypsum is produced from flue gas desulphurization at electricity plants, and ashes of waste incineration plants are used (after further processing) in concrete products to replace sand and/or gravel. Although these examples demonstrate the possibility of high end use of secondary flows, one also wants to avoid environmental risks resulting from the use of these secondary flows. As building materials often have a long lifetime, potential effects of material degradation need to be included in the risk assessment (both from a structural point of view as from an ecological point of view). As building materials are often recycled or reused at their end-of life, these risks also need to be avoided in the secondary use of the circular building material, to prevent that future generations are faced with an environmental risk. KPI's for these ecological and structural risks can help to select robust circular building options.

3.1.2 Demands and KPI's for Climate resilience

Within the framework of buildings, climate resilience can be (or needs be) integrated in obligatory demands. Most climate changes (heavy rain, drought, heat and sea rise level) imply an increase in load on the structures, i.e. more often and stronger wind, more storm water within a short time span, etc. Within the existing framework of obligatory performance demands, there is a need to change the loads, and the frequencies of it, leading to an increase in robustness of the structure to maintain the same risks as today. The same counts for the design of a neighborhood and its infrastructure. To account for risks due to climate changes the neighborhood design needs to be based on more heat/drought and heavier rainfall, resulting in for example sunken drains. Beside obligatory demands, voluntary KPI's can be defined to appreciate additional climate resilience quality of neighborhoods, infrastructure and buildings. Examples of these voluntary KPI's are:

- Heat comfort (indoor and outdoor), for example expressed in hours within a certain temperature range
- Water bearing capacity, being additional capacity to further lower the risks for water burden due to heavy rainfall

Which KPI is selected depends on the ambitions of the contractor and the possibility to quantify a KPI given the available information. For example, it may be unfeasible to establish the heat comfort, but instead the albedo effect of light surfaces can be measured.

Beside direct impacts in climate resilience, building solutions may have additional societal benefits or costs. For example mineral building materials for pavement that are permeable for water can have the risk

for unwanted additional growth of vegetation. By specifying KPI's for these societal costs and benefits, different building solutions for climate resilience can be compared on their impact. The chapter on 'roofs' is more elaborate on the specification of KPI's. The list of KPI's can also be used for mineral building materials, to select the applicable (relevant) KPI's.

3.2 Technology description: readily available Breakthrough technologies supporting circular and climate-proof objectives

3.2.1 Technical developments: Circularity

Mineral building materials will most probably represent the major material volumes in the construction assignments of a city. These materials are abundant in various sectors of city development, e.g.: foundation layers under the transportation infrastructure, pavement materials, metals (Al, Cu, Fe, and Zn), bricks and concrete for building infrastructure and roofing materials. Over the last decade, developments have increasingly focused on the re-use of waste materials in construction works to prevent the use of virgin materials and to enhance the recycling of materials in general. Overall, the use of granular construction products (e.g. as foundation layers under transportation infrastructure) has led to a shift from (virgin) sand and gravel to more recycled materials like recycling granulate from construction and demolition waste and bottom ash from the incineration of municipal solid waste (MSWI bottom ash). The monolithic products (concrete, bricks) do also use waste materials but mainly to replace part of the ingredients of the product. For example, recycling granulates or MSWI bottom ash can be used to replace the sand/gravel part in concrete. The use of recycled building materials adds to the "circularity" of materials and, hence, of cities as today's recycling rate of building materials is high (>97 %). However, it should be realized that recycling is not always similar to circularity. When the building material can be re-used only a single time in a downgraded application, the question arises whether this is circular. Today, about 95% of the recycled concrete, for instance, is used as aggregate for road foundations. Only 2 % is used as aggregates in (mostly nonstructural) concrete. The industry, the scientific community and policy maker's start addressing the question of multiple life cycles for these materials to enable and to ensure that the materials are technically and environmentally suitable for re-use in multiple life cycles.

Also for bricks (as building component), recycling rates are low. Recycling and designing for recycling of building components like beams and facades is just at its infancy. Better recovery and a higher value re-use is therefore one of the ambitions.

The versatility of concrete and other mineral based building materials is incredible, and there are hardly any limits with regard to the forms that can be made, properties that can be given and environments it should be able to serve. Readily available technologies are grouped into three circular pathways: reduce (material use), re-use (component instead of materials) and recycle.

- Reduce (material use) measures: the use of high strength / high performance concrete lead in general to less use of material for the same (service life / strength) performance demands. In principle, concrete is designed to match the demanded service life exactly, i.e. not too little performance as this leads to damage and maintenance, if not worse, and not too much, which is a waste of money. In combinations with high quality materials, service life of 250 years can nowadays be reached.
- Re-use (component instead of materials). Re-use of components is preferred over re-use of the materials because often more energy and possible production of waste from processing is prevented. Mineral building materials can be applied for modular building combining for instance elements with different properties. Modular building can be achieved by means of e.g. click joints (Click Brick) & LEGO blocks, Retractable joints or Jointless coupled elements. These developments enhance the potential for re-use of the components instead of recycling of the materials of which these components are made.

- Recycle. Within the recycle measures, examples of readily available breakthrough technologies are:
 - o Recycling of brickwork with brick recovery; broken or partly recovered bricks are milled and cold bonded into new bricks
 - o Recycling of construction and demolition waste into recycling aggregates for construction works (End of waste regulation in the Netherlands)
 - o 100 % waste based concrete (e.g. geopolymer concrete based on low-calcium or alkali-activated binders and recycled aggregates or aggregates from waste streams for which no other application could be found)
 - o Recycled gypsum plates
 - o Recycling of municipal solid waste incineration bottom ash (after thorough quality improvement technologies) in road foundation layers or as sand/gravel replacement in concrete.
 - o For foundations, in-situ stabilization or immobilization of (polluted) soils is possible.

The degree to which the above examples can be considered “circular” depends on the potential for re-use of these materials in multiple life phases. This subject can be matter of discussion (see above) and is basically related to the definition of circularity. This report does not discuss the definition of circularity in great detail. However, circularity is not a goal in itself but rather a means to obtain sustainability and to ensure acceptable environmental impact of construction materials.

3.2.2 Enabling developments: Circularity

Legislation to avoid ecological risks

The emissions of contaminants from construction products need to be acceptable for soil and groundwater in order not to contaminate the environment. Therefore, environmental regulations need to be in place that ensures protection of the environment. In the Netherlands, the (re-)use of construction products (that come in contact with rain water) is regulated under the Soil Quality Decree (2007). The clear environmental regulation, specification of test methods and quality control systems have led to a good re-use market and has led to the development of several innovative products/technologies. Examples of established re-use applications and materials are given in Table 3.1.

However, the developed tools and KPI's do not yet include the environmental performance (leaching of contaminants) in first and next life phases of the material. The emission of contaminants is dependent on the use (granular or monolithic) and time (alkaline materials change by uptake of CO₂). Therefore, it is difficult to assess the potentially changing effects of construction products on the environment. Since these criteria are relevant when assessing circularity, there is a need for additional knowledge and tools to judge feasibility of re-use in a next life phase from an environmental point of view.

Table 3.1 Examples of some major construction applications and the use of secondary materials in the Netherlands.

Application	Re-used material in application
Road foundation	MSWI bottom ash, LD steel slag, recycling granulate, phosphorous slag
Asphalt	Recycled asphalt granulate, coal fly ash, MSWI fly ash
Concrete	Recycling granulate, MSWI bottom ash, coal fly ash
Pavement stones	Recycling granulate, MSWI bottom ash

Legislation on sustainability of building materials

For new buildings it is obligated in the Dutch building regulations to calculate the greenhouse gas emissions and resource use related to material use for the building over its life cycle. In 2018 maximum requirements will be set for building related greenhouse gas emissions and resource uses. Circular building practices do have the potential to result in both lower CO₂ emissions and resource consumptions. By assessing and comparing these two obligated KPI's for circular building options, building solutions with the best performance can be selected.

Green procurement

For infrastructure, sustainability (or other societal benefits) is more often rewarded in green procurement. The most economically advantageous tender (MEAT) criterion enables the contracting authority to take account of criteria that reflect qualitative, technical and sustainable aspects of the tender submission as well as price when reaching an award decision. In the Netherlands authorities, contractors and knowledge bodies are cooperating in 'Duurzaam GWW'. In this Green Deal agreement is achieved to incorporate sustainability ambitions in procurement. In this approach the software tool Dubocalc is often used to be used to specify the 'MKI/ MilieuKosten Indicator' which is a weighted score of environmental impact. Circular building options have the potential to lower the MKI.

Green deals

Green Deals are agreements between the central government and other parties. Those other parties are companies, civil society organizations and other governments. The Green Deal helps to carry out sustainable plans. The national government can for example make an effort to adapt (obstructing) laws and regulations. In the green deal Cirkelstad, cooperation's are made between local authorities and companies in the building sector. The ambition is to increase circularity in the building sector in that region, by for example create storage to stock secondary building material, incorporate circular building ambitions in procurement and by creating field labs for new circular building technologies.

Urban metabolism and Concrete design tool

By combining data sources in cities, databases and models for economic activities and models for product studies, it is possible to create an overview of (secondary) flows through a city or region and how these flows develop over time. In addition, an overview of the (future) building activities can be made. Ideally for circularity, these secondary flows are used in a structural and environmental safe way to (re)build buildings and infrastructure.

Urban metabolism tools (future building needs/ generation of secondary flows) can be combined with a numerical concrete composition design tool based on performance demands. With the use of this tool, an inventory is made of the properties of secondary flows, predicting the performance properties of the final

mineral building product. These properties include: weight, thermal properties, mechanical properties and environmental (LCA) impacts, up to a declared value to 1 m³ of concrete.

3.2.3 Technical developments: Climate resilience

Climate adaptation in cities can be largely divided in two aspects: adaptation measures to reduce heat stress and measures to reduce problems with storm water. When these problems are related to building materials, a number of potential solutions can be summarized. Cities can be substantially warmer than the surrounding rural areas because of the use of more and different materials in the city. In addition, cities usually have more high rises, more people, more transport, industry and power plants. The building materials can adsorb heat and this contributes to the heat island effect in cities. Therefore, the construction industry, architects and spatial planners have already started to use more heat reflecting surfaces (white materials) to stimulate the albedo effect. Introduction of “green” (plants) and/or “blue” (water) roofs and surfaces on ground level can also contribute to reduce heat stress (see also chapter 4). Solar thermal collectors and/or PV solar panels can contribute to the absorption of heat and can be used as a sustainable source of heat and electricity.

Another development in the construction products sector is the production of water-passing and/or -permeable pavement stones. These products aim to enhance the discharge of storm water in the underlying soil and groundwater system. There are roughly three types of pavement stones with water-passing and/or -permeable properties: porous stones, open structure stones and stones with larger joints between the stones to enable fast infiltration of storm water in the underlying soil. Figure 3.2 shows some examples of the different types of water-passing pavement stones.



Figure 3.2 Examples of water passing and -permeable pavement stones: water-permeable stone (A) open structure stone (B) and stones with large joints (C).

For the concept of (climate) adaptive and circular construction materials, a combination of the use of secondary materials and water-passing and/or -permeable stones seems to be an optimal solution. However, the use of water passing and -permeable stones puts some requirements to the use of the construction with regard to the maximum loading/traffic density.

These type of solutions need to be assessed taking into account the expected amount of water discharge to the soil system and the water permeability of the existing soil system in the city. For example, when the soil system is mainly of a sandy type, the water infiltration will be much faster than when the soil system is mainly clay. Buffering layers of sand (or granular secondary materials) can then be applied as a temporary water storage layer.

3.2.4 Enabling developments: Climate resilience

In the project Climate Proof Cities (REF), assessment methods have been developed to assess vulnerability for climate change of neighborhoods (buildings/ infrastructures) and their habitants. These methods and tools can be used to (re)design neighborhoods for increased climate resilience. In this design different climate adaption can be assessed and combined, thus selecting effective measures. Some of these measures are on the level of buildings or streets. For example what the impact is of water permeable

pavement structures, white surfaces (Albedo) or water bearing capacity of built object. However as the geographical focus of most climate resilient tools is the neighborhood scale, the tools are not suitable to select appropriate measures for one building or street only.

3.3 Developing a business model

The Building sector is often characterized as 'traditional'. Green procurement has demonstrated to be effective to invert 'The circle of blame' - where building owners complained that there are no sustainable alternatives and builders complained that no one wanted to invest in sustainable building solutions. Lessons learned how to invert 'the circle of blame' for sustainable building can also be applied for circular building. Investments in new technologies for circular building will only be done when there is a sound business case. Therefore regulations, green deals and green procurement are needed to create a market for circular building (materials) and to give room to breakthrough developments for circular buildings (both technological and enabling).

Circular building needs innovation for more high-end use of secondary flows and to facilitate circular building in the future. Innovation is related to risks. Field labs and validation of new technologies are essential to shorten 'time to market'.

Innovations and the competition with established building solutions are also subject to economy of scale. Here there are two dimensions:

- Markets for (production) bulk materials for buildings and infrastructure and also for handling of secondary flows are at a European and sometimes even global level. From this perspective circular building technologies need to be beneficial on these market levels. Regulation is therefore a powerful mechanism, albeit that these regulations should be valid throughout Europe or even world-wide. However, this is normally a long and complicated process and EU regulations are often interpreted differently when implementing them in the Member States. This will still create barriers that prevent material trading over the borders of Member States. Therefore, the Dutch government uses their European Chairmanship of the EU to initiate a material roundabout around the North Sea area (North Sea Resources Roundabout). With this initiative, barriers due to different interpretation of legislation will be removed to stimulate the market for (secondary) materials in this area.
- Bulk materials for building and also secondary flows have a low profit margin. Logistics or additional labor costs can make or break the business model. On a regional level, it might be easier to overcome such costs and to find appropriate business models. The business model of cirkelstad for example is to separate demolition waste in more 'flows' that are more suitable for high-end recycling. The additional labor for material separation comes from reintegration of unemployed people that previously received an alimony from the local government. The contractor is guaranteed a market for cirkelstad through assignments of housing cooperation's in the region, thus the contractor could permanently employ more people.

Which geographical scale is more appropriate does not only depend on the type of breakthrough technology. It also depends on where leadership and ambition for circularity among the crucial stakeholders can be found.

4 Green Roofs

4.1 Construction assignments for roofs

Since roofs are often left unused, there is a great potential and surface area available for adding value to the built environment. However, roof adjustments are requiring a challenging business model as the benefits and costs are not related to one party. The benefits of green roofs are mostly found on the urban scale, as the costs of green roofs are appointed to the owner of the estate. This means that there is a growing demand of creating business models that bring together the benefits and costs.

In paragraph 4.2 we analyse the current needs of the market for a business model in order to determine the focus of this study; developing a rooftop impact model (paragraph 4.3) In 4.4 we shortly discuss constructive requirements for different rooftop types and in 4.5 we mention innovative technologies with regards to climate resilient and circular roofs. In 4.6 we consider relevant aspects regarding investments in rooftop adjustments after which we close off with conclusions in paragraph 4.7.

4.2 Market need

4.2.1 Stakeholder needs

To analyze the actual needs of stakeholders with regards to rooftop adjustments, meetings of the Green Deal “Green Roofs” have been attended and participants have been contacted. This Green Deal has created commitment between different stakeholders to organize a force team that has set the goal to enlarge the application of Green Roofs in the Netherlands. The Green Deal is a cooperation of public parties (government, municipalities), knowledge and research institutes, architects, green roofs businesses, water cooperation’s, ngo’s and banks.

Consultation among stakeholders of the Green deal “Green Roofs” revealed that their primary questions are related to;

- Advice on suitable locations for green roofs;
- More in-depth information on the effects of green roofs, provided by independent organizations;
- Better perception of the financial implications.

4.2.2 Adaptation support tool

The adaptation support tool has been developed for analysing the climate effects of spatial interventions. The tool gives early in the development process an indication of the different options and effects of climate adaptation measures. When early in the development process, the tool can give local climate solutions according to preselected preferences on neighbourhood scale. This tool contains 55 climate solutions on concerns such as heat stress, water retention and air quality. This tool is evidence based, which means that all figures on the performance level are supported by scientific analysis and practise. The adaptation support tool can be used for scenario studies, cost-benefit analysis, conceptual design studies and stakeholder sessions.



Figure 4.1 Adaptation support tool developed by Deltares, Alterra, Wageningen UR and Bosch and Slabbers landscape architects.

The adaptation support tool is specialized on the local effects of climate adaptation interventions on neighborhood scale. In this project we will focus on the effects of adaptive circular rooftop types, and the impact on building level.

The TO2 institutes concluded that their contribution to the rooftop discussion would be most valuable when bringing together the available information on the effects and effectiveness of various rooftop solutions.

4.3 Impacts of rooftop adjustments

4.3.1 Indicator framework

The relevant effects and impacts of rooftop solutions are determined in the light of the overarching TO2 project Adaptive Circular Cities (ACC). The objective of ACC is to contribute to a breakthrough in cross sectorial investment decisions regarding urban concepts that take into account climate resilience, mitigation and resource efficiency. Key performance indicators for rooftop solutions should therefore focus on these three topics, and related impact categories (Table 4.1). To assess these impact categories, various indicators can be defined and examples of these are shown in the table. Each indicator has different characteristics with regards to e.g. relevance, data availability, reliability and familiarity. It is therefore important to discuss which indicators are best suited for which use case.

Table 4.1 KPIs for adaptive circular cities

Impact area	Impact category	Indicator
Mitigation	Global warming	Greenhouse gas emissions (kg CO₂-eq.)
Adaptation	Heat stress	- Overheating indoors (hours) - Reduced air temperature outdoors ((ha's of) °C below reference) - Improved thermal comfort outdoors ((ha's of) PET °C below reference)
	Biodiversity	Increase of amount red list species
	Water nuisance/flooding	- Water retention (m³; % of local retention needed) - Infiltration (% of unpaved surface; m³ of infiltrated water; % of infiltration needed) € saved
	Drought	
Resource efficiency	Energy	- Energy use (MJ final energy; €) - Share of waste and renewable energy (% of consumption) - Renewable energy production (kWh; % of consumption) - Embodied energy (MJ/kg)
	Materials	- Materials used (kg) - Share of recycled/bio-based materials (% of consumption) - Share of recyclable materials (% of consumption) - Life time (years; extended life time) - Waste (kg/capita)
	Water	- Consumption (liters per capita) - Share of reuse (% of consumption)
	Food	Food waste (% of food produced)

To evaluate the added value of various rooftop solutions, a relevant set of indicators, based on Table 4.1, has been selected in Table 4.2. Some indicators, like 'waste', are less relevant for rooftops, because a roof in principle doesn't produce waste like a household. Additionally, the waste that is produced is organic waste and has potential reuse in energy or biomass cycles (such as biogas). Other indicators have been added, like real estate value and biodiversity, as they are necessary to give a complete picture of all the benefits of a roof and are thus relevant for the value case/business case of a rooftop.

In the next paragraph, information on these indicators available at the TO2 institutes has been brought together to estimate the effectiveness of a certain rooftop type on these impacts

Table 4.2 KPIs for rooftop solutions

Impact area	Impact category	Indicator
Mitigation	Global warming	• Greenhouse gas emissions (kg CO ₂ -eq.)
Adaptation	Heat stress	• Overheating indoors (hours) • Reduced air temperature outdoors ((ha's of) °C below reference)
	Water nuisance/flooding	• Water retention (m ³ ; % of local retention needed)
	Drought	
Resource efficiency	Energy	• Energy saved (kWh; €) • Renewable energy production (kWh; % of consumption)
	Materials	• Materials used (kg) • Share of recycled/bio-based materials (% of consumption)
	Water	• Potential for reuse (m ³)
	Food	• Production of food (kg; €)
Other	Biodiversity	• Species (#; % change)
	Experience	• Societal value (recreation, education)
	Real estate	• Real estate value (€; % of price) • Image (extra customers; extra turnover; goodwill)
	Biomass production	• Production of materials (kg; €)
	Health	• Air quality (kg air treated)

4.3.2 Rooftop impact model

As part of the ACC project, the rooftop impact model has been developed as a first attempt to quantify the effectiveness of various rooftop solutions. To realize this, the existing knowledge of the research institutes involved, TNO, Wageningen University and Deltares, has been combined in one table showing the interactions between rooftop solutions and different impacts (Figure 4.2). The underlying assumptions for this model are explained extensively in the following paragraphs.

type	Unit	Green roofs				
		Vegetation height 0-5 cm; substrate layer max 5 cm	Vegetation height 5-20 cm; substrate layer 5-15 cm	Vegetation height 20-50 cm; substrate layer 15-30 cm	Vegetation height 50-100 cm; substrate layer 30-50 cm	Vegetation height > 1m; substrate layer 50-200 cm
Effects						
Embedded energy - Solar collector system	GJ/m ²		3.53			
Avoided CO ₂ -emissions - electricity PV	kg/m ²					
Avoided CO ₂ -emissions - electricity wind	kg/turbine/yr					
Avoided CO ₂ -emissions - solar collector	kg/m ² yr					
Biodiversity	Index			12	12	12
Experience	Score 1-4 4 highest					
Experience quality (including sensory perception) vision eyelevel		2	3	3	3	4
Experience quality (including sensory perception) vision horizon		2	2	2	2	4
Real estate value						
Value of real estate	l		0	0	0	0
Rental prices	l		0	0	0	0
Air treatment/water filtering						
Air treatment	kg/m ² yr		0.001		0.001	0.001
Nitrogen uptake	kg/m ²		0.0015	0.01	0.045	0.0006
Water purification	m ³					

Figure 4.2 Effectiveness model rooftops

It should be noted that this model is a first estimation of the quantification of the effectiveness of rooftop solutions and, though based on our best knowledge, definitively leaves room for improvement. The argumentation should be read carefully before applying the knowledge in practice. However, it can be considered a basis document from which to build upon.

When the impact of various rooftop solutions will be validated, this can form the base of creating healthy business models. If, for example, the amount of water storage is known of different rooftop solutions, this can give insight of the positive effect of water management at the building location in terms of flooding. Additionally, this model can eventually be used as a decision tool for rooftop solutions. The impact of different rooftop can be compared, in order to get to know the direct effect of design solution. Bottom up, the tool can propose solutions related to defined goals.

In the impact model we have defined choices that are relevant for indicating the effect of the rooftop performance. In the following paragraphs we have been focusing on the *type of roof* in relation to the impact of the rooftop type. However, choices such as location which affects the amount of sunlight and rainfall amongst others require further study. Additionally, information about the construction, such as span length and construction type, influence the decision criteria for the type of roof, as water storage will require a heavier construction in comparison to sedum roofs.

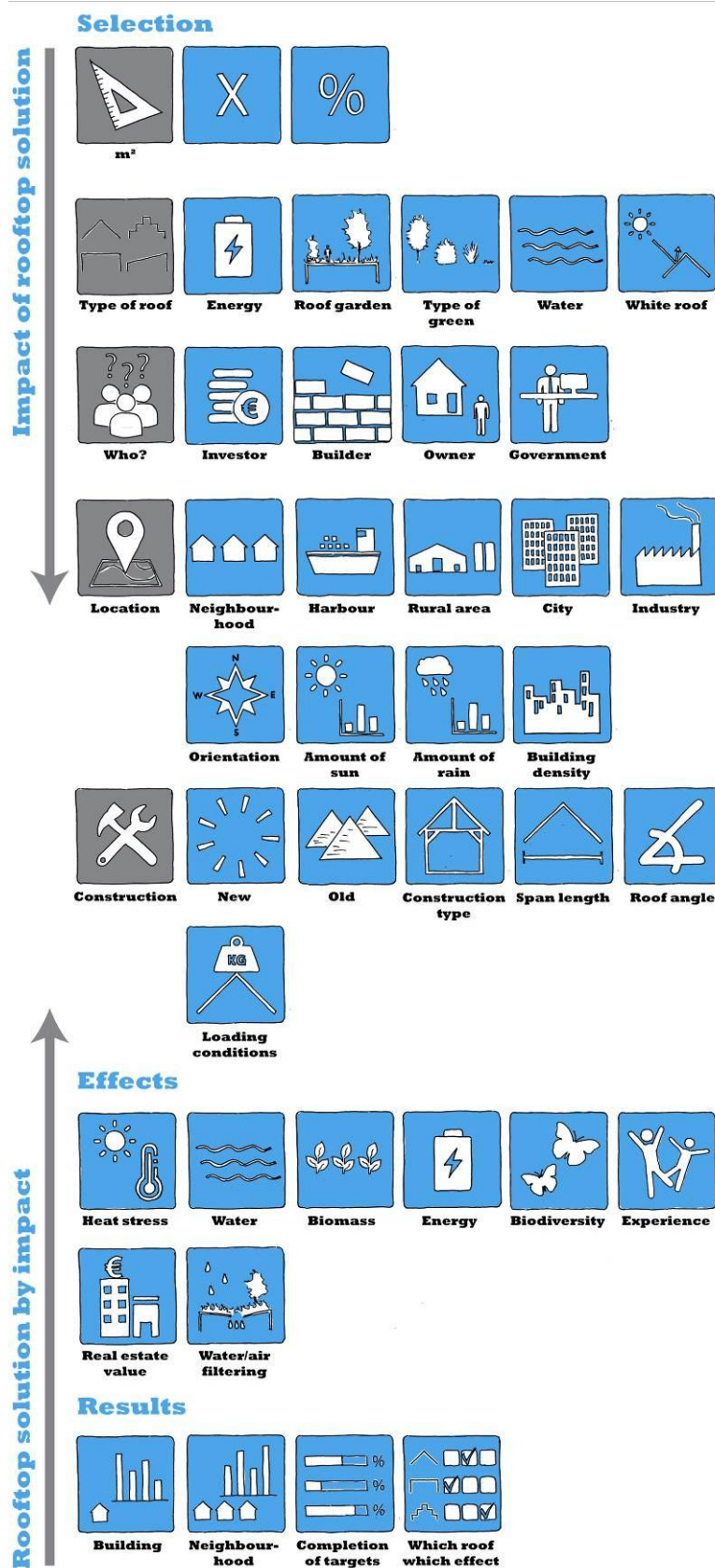


Figure 4.3 Rooftop impact tool

The impact model should be possible to be used on two different ways. Top-down, design criteria can be selected, after which the impact of this selection will be given on building level and neighborhood level. The impact of different selections can be compared in order to identify the different effects of the different roof types. Bottom-up, different goals and effects can be defined, after which different rooftop solutions, and combination of different solutions, can be given. The model can indicate the amount of percentage of the required effects will be met. This means that the impact model can be used as a decision tool for rooftop solutions.

Heat stress

Adjustments to the rooftop can have an influence on the temperature indoors and outdoors with the possibility to reduce heat stress and energy consumption.

Green roofs - indoor temperature

Green roofs might reduce the heat transfer from outdoors to indoors due to (1) a different reflection factor for shortwave radiation (albedo value); (2) an increase in the thickness of the insulation layer; (3) an increase in the convective heat transfer; and (4) evapotranspiration. However, in simulation studies by Van Hooff et al (2014), the number of overheating hours stays more or less the same when applying an extensive green roof. The positive effects are countered by the adverse effect that extra insulation brings. The effect of applying a green roof is greater the lower the insulation rating of the building's shell is.

- Van Hooff, T., Blocken, B., Hensen, J.L.M., Timmermans, H.J.P. (2014). On the predicted effectiveness of climate adaptation measures for buildings. Building and Environment 82: 300-316.

White roofs – indoor temperature

Simulation studies by Van Hooff et al. (2014) investigated the effect of lighter roofs on the indoor temperature of Dutch dwellings. The main factor influencing this effect appeared to be the degree of insulation of the building. Increasing the albedo of a roof from a terraced house from the seventies could reduce the amount of overheating hours indoors by 50%. For a similar dwelling built in 2012 this figure would be 14%. It is assumed these houses are not actively cooled, so a whiter roof would not lead to a reduction in energy consumption for cooling.

However, in winter, a higher albedo in colder climates could increase the energy demand for heating by around 2% for the 2012 dwelling and 7% for the dwelling from the seventies. To calculate the increase in energy consumption and costs, the figures for average energy consumption of 'milieucentraal.nl' have been used:

- A terraced house from the seventies uses on average 2700 m³ of gas per year
- A terraced house built in 2000 consumes on average 1200 m³ of gas per year

Three quarters of this consumption is for heating. With an energy price of 0,62 ct/m³ (milieucentraal.nl), the energy costs for a terraced house with a white roof would increase with €87,89 (142 m³ gas) for the seventies dwelling and €11,16 (18 m³ gas) for the house of 2012. Extra CO₂-emissions amount to 252 kg CO₂ for terraced house from the seventies and 32kg CO₂ for the 2012 dwelling, assuming an emission factor of 56,24 kg CO₂/GJ (Folkert & Wijngaart, 2012).

- Van Hooff, T., Blocken, B., Hensen, J.L.M., Timmermans, H.J.P. (2014). On the predicted effectiveness of climate adaptation measures for buildings. Building and Environment 82: 300-316.

Green roofs - outdoor temperature

Computer simulations of green roofs have not resulted in a noticeable reduction of air temperatures at pedestrian level (Gromke et al., 2015). The cooling effects are limited to the direct surroundings: Wong et

al found a temperature difference of a few tenths of a degree at a height of 1 meter. Gromke et al. (2015) simulated the conditions for a street in Arnhem and found no temperature differences at 2 meters height. For the rooftop model developed in this study it is therefore assumed that a green roof has no effect on the outdoor temperature.

- Gromke CB, Blocken B, Janssen WD, Merema B, van Hooff T, Timmermans HJP. (2015). CFD analysis of transpirational cooling by vegetation: Case study for specific meteorological conditions during a heat wave in Arnhem, Netherlands. Building and Environment. doi:10.1016/j.buildenv.2014.04.022.
- Wong NH, Chen Y, Ong CL, Sia A (2010). Investigation of thermal benefits of rooftop garden in the tropical environment. Build Environ 2003;38:261e70)

White roofs - outdoor temperature

Measurements by Van Hove et al. (2014) in Rotterdam have not indicated a clear relation between the average albedo of surfaces and the average air temperature in the surrounding of measurement instruments. Computer simulations by Kleerekoper et al. (in review) do show a cooling effect of 0,5-1°C at 2 meters height when changing the color of the roof from black to white. Because the effect within a few meters of the roof is not that relevant (since you don't use a white roof as you might use a green roof for recreation), it is assumed for this model that the effect of white roofs on outdoor temperature is not significant enough.

- Van Hove, L.W.A., Jacobs, C.M.J., Heusinkveld B.G., Elbers, J.A., van Driel, B.L., and Holtslag, A.A.M. (2014). Temporal and spatial variability of urban heat island and thermal comfort within the Rotterdam agglomeration. Building and Environment. DOI: 10.1016/j.buildenv.2014.08.029
- Kleerekoper, L., Dobbela, A.A.J.F. v. d., Bruin-Hordijk, T.D., Dorst, M.J. v. (in review), "Climate adaptation strategies: Achieving insight in microclimate effects of redevelopment options". Submitted to the Journal of Smart and Sustainable Built Environments.

Water roofs

It is assumed that the effect of blue roofs on the indoor temperature is similar to effect of green roofs and therefore not significant. In contrast to green roofs, blue roofs can use the full potential for evaporation, transforming radiation energy into evaporation of the water, thereby reducing the amount of energy available for heating of the atmosphere, and thus lowering the outdoor air temperatures over evaporating surfaces. Important requirements for the effectiveness of blue roofs are that; 1) water is available on rooftops during heat waves; 2) the temperature of the water is below the air temperature (also during the night). Otherwise the water may increase the air temperature.

Simulations with Computational Fluid Dynamics (CFD) have shown that the air temperature at 0.5 meter above the water surface can decrease by 2.7°C to 3.9°C (Toparlar, 2012). The effect is, however, very local and we assume that the roof itself is not being used, as in the case of white roofs. Therefore, it is assumed that the effect at street level is insignificant. If a city, however, has a large surface of blue roofs, this will have an effect on the average outdoor temperature and the urban heat island effect.

- Toparlar, Y. (2012). Computational analysis of climate change adaptation measures at the building and street scale focused on evaporative cooling: Case study for Bergpolder Zuid. Master thesis, Eindhoven University of Technology. Supervisors: Twan van Hooff, Wendy Janssen, Hamid Montazeri, Harry Timmermans, Bert Blocken, Ronald Albers.

Pluvial flooding

Green and blue roofs can contribute to reduce pluvial flooding from extreme rainfall, both in volume and in frequency. Extreme rainfall in this study is defined as rainstorm events larger than 30 mm within a few

hours. In the Netherlands the maximum recorded rainstorm is in the order of 150 mm (i.e. 1500 m³/ha). The quantity of this contribution depends very much on the roof setup. The growing media of green roofs hardly delay the rainfall excess water from running off. Relevant runoff delay on roofs (green or blue) can only be accomplished by additional contraptions (temporarily) preventing the water to runoff or slowly releasing the water. These types of roof can also be emptied much faster; 50-100 mm in one or a few days (or maybe even in minutes, if the capacity of the sewage system allows it). They are, therefore, available more often and much more effective.

Vegetation of rooftops can create a sponge effect, by absorbing water during rainfall. . The kind of vegetation and substrate layer is related to the amount that can be absorbed. The water will be vaporized by air or absorbed by vegetation and vaporized by the stomata of the leaves. In Dutch summers, it takes a week to vaporize 20 mm of water. This makes them much less effective than roofs with delayed run-off systems.

It should be mentioned that there should be taken a maximum water storage capacity in mind. The dimensions of the roof, as well as the used system setup define the water storage capacity. This means that during extreme rainfalls the roof can work as a water buffer, but that eventually the water problem will not be solved completely.

Green roofs – water storage

Most relevant parameter is the storage capacity in the growing medium (the substrate layer). In addition water can be stored in (part of) the drainage layer as well. The storage capacity of the growing medium depends on the composition and the thickness of the substrate layer. In this study we do not consider the composition of the substrate layer. In addition we assume that a green roof is not equipped with a delayed runoff system. In addition we assume a minimum thickness (4 cm) below which green roof cannot function properly.

The actual storage capacity of a green roof can vary between 0 (right after a large rainstorm when the substrate layer is still fully absorbed with water) and the physical capacity (after a long dry period). For growing media thicker than 50 cm we assume a minimum available capacity of 10 mm. These kind of green roofs normally have a different setup. Maximum storage capacities vary from 25 liters/m² green roof for a substrate thickness of 4-15 cm to 100 liters for a substrate of 50-200 cm.

Water roofs – water storage

For a rooftop, specifically designed to store water, we assume a minimum roof depth of 2 cm and a maximum of 15 cm. This is independent of the fact of the runoff can be delayed or not. Roofs with more than 15 cm water storage require modified (heavier) roof constructions.

Stored water on roofs without delayed runoff can (like green roofs) only be removed by evaporation. This implies that the available storage can vary between 0 and the maximum storage capacity of 150mm for a roof depth of 15 cm (1500 m³/ha = 150 mm). For roofs that slowly release (delay) the water we assume always a minimum available storage at the start of the rainstorm (15 mm). Most likely this minimum value will be higher. However that depends on the way the runoff is delayed.

Water roofs – water harvesting

Roofs can also be used to collect water and use it at a later stage, e.g. for gardening. This is called water harvesting. For harvesting, rainwater that falls on the roof can be transferred (whether delayed or not) to a storage facility. If the storage capacity is sufficient, all the water falling on the roof during a rainfall event might be captured and stored and not running into the sewage system or onto the street. The potential for water harvesting is, therefore, dependent on the storage capacity and the actual amount of rainfall. Unfortunately, this makes it impossible for this study to determine the potential in advance and in generic terms.

Production of biomass

The production of biomass on green roofs should be considered a bonus. The amount of biomass is relatively low and cannot be seen as a business case. Vegetable, fruit, herbs and other biomass such as honey and resources give harvests of 0.2 kg/m²/yr by small vegetation heights between 0 and 0.2 cm. At vegetation heights of 20-50 cm harvests can be found of 0.2-1 kg/m²/yr, at heights between 50-100 cm the harvest will be estimated between 1-2 kg/m²/yr by and 0.2-0.5 kg/m²/yr by heights larger than 100 cm. The latest category is only given for trees. It should be mentioned that a combination of different vegetation, such as trees and vegetables, are expected to give higher results of biomass harvest.

This data is derived from biomass production on solid ground based on parameter value of the vegetation succession model SUMO (Wamelink et al. 2000 and 2009). This model is based on a literature review of different vegetation and locations. Additionally, an expert estimate has been made in order to translate this knowledge to a roof condition. It can be assumed that vegetation is experience harder conditions on roofs in terms of climate and ground condition in comparison to solid ground.

Although the quantities of biomass production on green roofs are relatively small, by combining values such as restaurants with small scale and local consumption of locally grown food, the biomass production can give a valuable bonus.

In this category, carbon capture is also considered biomass. Plants use CO₂ as an energy source and as building material. The amount of CO₂ plants can capture is strongly dependant on the local conditions such as temperature, rainfall, hours of sun shine and soil fertility. The circumstances of green roofs are relatively poor, so the carbon capture will be low. The carbon capture of green roofs is similar to lawn, rose beds and green roofs. They estimated that a hectare of green roof will capture about 8 tons of CO₂ in 40 years. This is comparable to what with two average urban trees will capture in 40 years (Aalbers, 2012). The amount of carbon capture is related to the type of vegetation. Heather is capturing more carbon in comparison to grasslands, but less than small bushes. The given values of carbon capture in the rooftop impact model are based on the SUMO model and translated to roof conditions (Wamelink et al. 2000 and 2009).

- Aalbers, C.B.E.M. , de Vries E.A. and Kopinga, J. 2012. CO₂-compensatie in openbaar groen in Nijmegen. Alterra, Wageningen.
- Wamelink, G.W.W., Mol-Dijkstra, C.J.P., Dobben, H.F. van, Kros, J. & Berendse, F. 2000. Eerste fase van de ontwikkeling van het Successie Model SUMO 1. Verbetering van de vegetatiemodellering in de Natuurplanner. Rapport 045. ALTErra, Wageningen.
- Wamelink, G.W.W., Dobben, H.F. van, et.al. (2009) Effect of nitrogen deposition reduction on biodiversity and carbon sequestration. Forest Ecology and Management 258: 1774–1779.

Production of energy

Roofs can be used for the production of renewable energy. Here, energy production by solar panels, a small wind turbine and a solar collector system is considered.

Photovoltaic

On average, PV panels in the Netherlands produce 875 kWh/kWp, taking into account that not all panels are positioned in an optimal orientation towards the sun (Sark, 2014). With a current peak capacity of 160 Wp/m² (Vreugdenhil, 2014), a square meter of PV panel produces on average 140 kWh per year. Assuming an energy price of €0,22 per kWh (milieucentraal.nl), a m² of PV would produce electricity worth €30,80. A GJ of electricity emits on average 155,83 kg of CO₂ (Folkert & Wijngaart, 2012), meaning a m² of PV saves 78,54 kg of CO₂ per year. In addition, the embedded energy of a solar panel has been taken into account. Using the Cumulative Energy Demand method applied to the Ecoinvent 3.0 database and SimaPro 8.0.6 software, the embedded energy for a m² of a PV system amounts to 4,5 GJ (Frischknecht et al., 2007). This

is the average of a whole PV system mounted on a flat roof (including 23 m² of PV modules (multi-Si), inverter and PV mounting system).

Green roofs can increase the performance of solar panels. The efficiency of solar panels decreases with higher air temperatures. As vegetation on roofs reduces the ambient temperature through evaporative cooling, the output of solar cells can be improved. Two studies suggest a 6% increase in production in Berlin (Köhler et al., 2007) and 3% in New York (Perez et al., 2012). Taking the average, this study assumes a production increase by 4,5% per year. This would amount to an extra production of 6,3%, €1.39 and a reduction of 3,53 kg CO₂ per year.

- Köhler, M., Wiartalla, W., Feige, R. (2007). Interaction between PV systems and extensive green roofs. Fifth Annual Greening Rooftops for Sustainable Communities Conference, Minneapolis, 2007.
- Perez, M.J.R., Wight, N.T., Fthenakis, V.M., Ho, C. (2012). Green roof integrated PV Canopies – An empirical study and teaching tool for low income students in the south Bronx. Bronx Design and Construction Academy
- Frischknecht, R., Jungbluth, N., Althaus, H.-J., Doka, G, Heck, T., Hellweg, S., Hischier, R., Nemeck, T., Rebitzer, G., Spielmann, M., Wernet, G. (2007). Overview and Methodology. Ecoinvent Report no. 1. Swiss Centre for Life Cycle Inventories, Dübendorf, 2007.

Wind turbine

Various types of wind turbines for rooftops exist¹. The province of Zeeland, the Netherlands, has tested various small wind turbines varying in capacity from 0,5kW to 6 kW² (Province of Zeeland, 2012). For this example we base our calculations on the average production of these turbines, which is 664 kWh per year, though the differences between the turbines are large and in the range of 49-2.352 kWh/year (the production per kW capacity also has a broad range of 36-1.015 per kW). It has to be noted, however, that these turbines have been tested in open field. Different conditions apply in urban environments. Also, the actual energy production of small wind turbines is largely debated. Therefore, these figures have to be treated with care.

With an energy price of €0,22/kWh the turbine would generate €146,08 worth of energy per year. In addition, it would save 372,5 kg CO₂ with an emission factor of 155,83 kg CO₂/GJ (Folkert & Wijngaart, 2012). Finally, the embedded energy of a 750 kW wind turbine has been calculated to amount to 8.738 GJ, providing a rough indication of 11,7 GJ embedded energy per kW for a wind turbine (using the Cumulative Energy Demand method applied to the Ecoinvent 3.0 database and SimaPro 8.0.6 software) (Frischknecht et al., 2007).

- Provincie Zeeland (2012). Testveld Kleine WindTurbines Zeeland. ZEE1300980.
<http://www.zeeland.nl/digitaalarchief/zee0801257>

¹ <http://www.duurzame-energiebronnen.nl/kleine-windturbines.php>

² <http://www.duurzame-energiebronnen.nl/subsidie-windenergie.php>

Solar collector

A standard solar collector system, covering 2-5 m² per household, produces on average 1,5 GJ of energy per m² per year (Leguijt & Schepers, 2013), saving 47,4 m³ of gas (assuming an energy content of 31,65 MJ/m³). With an energy price of €0,62/m³ gas (milieucentraal.nl) the system produces €29,38 worth of energy. The emission factor for gas is 56,24 kg CO₂/GJ (Folkert & Wijngaart, 2012), enabling the system to reduce CO₂ emissions by 84,36 kg/m². The embodied energy of the complete system (collectors, boiler, tubing, etc.) amounts to 5,3 GJ/m² (based on a 4 m² solar collector system) (using the Cumulative Energy Demand method applied to the Ecoinvent 3.0 database and SimaPro 8.0.6 software) (Frischknecht et al., 2007).

- Folkert, R., Wijngaart, R. van den (2012). VESTA – Ruimtelijk energiemodel voor de gebouwde omgeving – Data en methoden. PBL-publicatienummer: 500264001
- Vreugdenhil, C. (2013). Een studie naar de potentie van PV in Nederland. WUR, DNV-GL, PBL.
- Leguijt, C., B.L. Schepers (2014). Vesta 2.0 - Uitbreidingen en dataverificaties. CE Delft, Publicatienummer: 13.3440.45.
- Sark, W. van (2014). Opbrengst van zonnestroomsystemen in Nederland. Universiteit Utrecht, rapportnr CIER-E-2014-1.
- <http://www.milieucentraal.nl/energie-besparen/snel-besparen/grip-op-je-energierekening/energieprijzen/>
- Frischknecht, R., Jungbluth, N., Althaus, H.-J., Doka, G., Heck, T., Hellweg, S., Hirschler, R., Nemeck, T., Rebitzer, G., Spielmann, M., Wernet, G. (2007). Overview and Methodology. Ecoinvent Report no. 1. Swiss Centre for Life Cycle Inventories, Dübendorf, 2007.

Biodiversity

Compared to other green areas in the Netherlands a green roof is a harsh habitat to life. It can be very dry, and has very little soil. Roofs are not very comparable to the habitats normally found in the Netherlands. Therefore, exotic vegetation is used on green roofs. Additionally, the variety of species living on the green roofs will be smaller compared to natural habitats on ground level. However, it will more than the variety of species living on the alternative roof: a bitumen roof. Green roofs can be seen as an added greenvalue to the city. It should be noted that it cannot replace other forms of green and parks.

Extensive green roofs can offer all kinds of micro-organisms, mosses, herbaceous vegetation, insects spiders and birds a good habitat. Intensive green roofs offers shrubs, snails, amphibians and small mammals also a valuable habitat. Older green roofs will have more variety in heights and vegetation, which will lead to a wider variety of species (oberndorfer et al, 2007). Brenneisen (2003) counted on an old semi-intensive green roof 78 different spiders, 254 different beetles and many different birds. On a younger extensive green roof Kadas (2006) found 28 different spiders, 35 different beetles and many snails. In London, Jones (2002) found between 8 and 54 species of invertebrates on green roof. On a very young green roof (2 years) , 11 different species of insects were found (Smit, 2015)

Green roofs cannot only establish local habitats, but also function as Green Infrastructures, connecting green zones in dense urban areas. Connected green infrastructures will have a higher impact on the biodiversity in comparison to isolated green zones. Different types of vegetation will have a different impact on biodiversity of vegetation; heather and grasslands will lead to a higher biodiversity index of vegetation types (14, with peaks of 16) in comparison to small bushes and woods (around 12) (Wamelink et al 2009b). The higher the biodiversity index, the larger the possibility that red list vegetation types are found. The biodiversity index indicates the amount of different vegetation types per square meter.

It should be mentioned that these numbers are derived from solid soil indications, modelling of rooftop situations is possible but out of the scope of this project.

- Wamelink, G.W.W. , Dobben, van H.F. and Berendse, F. 2009b. Vegetation succession as affected by decreasing nitrogen deposition, soil characteristics and site management: a modelling approach. *Forest Ecology and Management* 258: 1762–1773.
- Brenneisen, S., 2003. The benefits of biodiversity from green roofs: Key design consequences, 1st North American Green Roof Conference: Greening rooftops for sustainable communities. The Cardinal Group, Toronto, Chicago, pp. 323-329.
- Jones, R.A. 2002. Tecticolous invertebrates. The invertebrate fauna of green roofs in urban London. *English Nature*.
- Kadas, G., 2006. Rare invertebrates colonising green roofs in London. *Urban habitats* 4, 20.
- Oberndorfer, E., Lundholm, J., Bass, B., Coffman, R.R., Doshi, H., Dunnett, N., Gaffin, S., Köhler, M., Liu, K.K.Y., Rowe, B., 2007. Green Roofs as Urban Ecosystems: Ecological Structures, Functions, and Services. *BioScience* 57, 823-833.
- Smit, A., B. de Vries, D.R. Lammertsma, T.A. de Boer en F.G.W.A. Ottburg, 2015. Groene daken in Tiel; Een onderzoek naar de betekenis van de groene daken op Ziekenhuis Rivierenland Tiel en R.K. basisschool de Achtbaan in Tiel. Wageningen, Alterra Wageningen UR (University & Research centre), Alterra-rapport. 28 blz.; 16 fig.; 4 tab.; 19 ref.

Experience

The experience of green environments is based on affective and cognitive aspects (Graaf, de et al., 2002). Where the affective experience is a basic emotion, initiated by primary reactions and based on earlier experiences, the cognitive experience is more rational and based on knowledge.

The sight on green vegetation has a positive impact on human wellbeing (Kaplan, 2001). Green has a positive influence on creative thinking, focus, health and productivity (Cooper, C. and Browning, B., 2015). Additionally, the window view of a work environment has a significant influence on the wellbeing of the employee, especially a varied vegetation structure adds to a higher wellbeing (Gilchrist, K. et al., 2015). Green roofs can deliver a larger impact on human wellbeing when the roof is accessible or can be seen from the indoor space. A variation of vegetation with different colours and heights has a more positive effect on the experience of roofs compared to vegetation such as sedum. Additionally, when the roof is accessible higher ratings are given to a more sensorial experience in terms of smell, colours or edible plants.

It should be noted that the given numbers are an estimated value of the amount of positive value scored between 1 (positive) and 4 (very positive). These numbers are indicated by experts based on the experience of green on people. It should be noted that further research is required for the different roof scenarios.

- Cooper, C. and Browning B. Human spaces : The global Impact of Biophilic Design in the Workplace, 2015 retrieved from www.humanspaces.com
- Gilchrist, K., Brown, C., Montarzino, A. (2015). Workplace settings and wellbeing: Greenspace use and views contribute to employee wellbeing at per-urban business sites. *Landscape and urban planning* 138: 32-40.
- Graaf, de R., Reinhard, S and Vreke, J. (2002). Belevingsgraadmeters. Rapport 7.02.03
- Kaplan, R. (2001). "The Nature of the View from Home: Psychological Benefits." *Environment and Behavior* 33(4): 507-542.

Real estate value

Urban green, like parks, nearby housing increase the property value with 4,5-15% (Bervaes, 2004) In this research green roofs were not taken in account, which means that these numbers cannot be linked to green roofs and can only give an indication of the property value. A Canadian study (Tomalty, 2010) did value the ecosystem services of green roofs and connect them to the property value. However, the chosen system does not match the current Dutch system, because normally benefits of green roofs are not part of

the assessment. The only exception is a green roof which can be seen as an extension of the outside living space. For example a private and accessible green roof. According to Tomalty this would be 7-11%. As green roofs can be seen as a form of insulation green roofs might be discounted in the energy labeling of houses. However, because it will be only one of many parameters the impact on the property value is relatively low.

The value of the view on green roofs for businesses has been validated by the work of Lee (2015). This research states that a micro-break of 40 seconds on a green roof will have positive effect on the sustained attention. When the view on roofs will lead to a higher productivity, this will be an interesting value for the real estate market. When adding this to the storm water retainment, energy saving, carbon fixation, experience amongst others, influence on real estate value is to be expected. The financial benefit requires further analysis.

- Bervaes J.C.A.M., J. Vreke, 2004. De invloed van groen en water op de transactieprizen van woningen. Wageningen, Alterra, Alterra-rapport 959. 65 blz. 33 fig.; 7 tab.; 13 ref.
- Tomalty, R., Komorowski, B., & Doiron, D. (2010). The monetary value of the soft benefits of green roofs. Canada Mortgage and Housing Corporation, Ottawa.
- Lee, K. , Williams, K., Sargent, L., Williams, N and Johnson, K. (2015). 40-second green roof views sustain attention: The role of microbreaks in attention restoration.

Air quality

Several model studies investigate the influence of increased deposition of pollutants caused by green on air quality (among others Nowak et al., 2006 and Yang et al., 2008). These studies assume that the dry deposition of a pollutant is a function of the deposition velocity, the height to which the pollutant is well mixed, and the concentration of a pollutant. The deposition velocity of green is in general higher than that of other urban surfaces due to the metabolic uptake by plants, the “stickiness” of the leaf surface, the large surface area of green, and the aerodynamic properties of green (Broadmeadow, M.S.J and Freer-Smith, P.H, 1996 cited in Pugh et al. 2012). This increased deposition velocity is also supported by measurements (among others Rondón et al., 1993 and Hesterberg et al., 1996). The higher the deposition velocity, the more deposition, and the lower the concentration of a pollutant in the air will become. The concentration itself also influences the deposition, the higher the concentration the more deposition. The study of Nowak et al. (2006) found that for ten American cities the estimated air quality improvement due to removal of pollutant by urban trees was 1 % or less. For the city of Portland, with 42% of tree cover, the air quality was 0.003% improved for CO, 0.6% for NO₂, 0.8% for O₃, 1% for PM₁₀, and 0.7% for SO₂.

In principal conifer vegetation is best in removing fine dust, because the dust is deposited on the needles and on the branches. Furthermore, conifer trees in general stay green throughout the winter, making it possible to remove fine dust all year round. For gases, vegetation with leaves with large stomatal openings removes most pollutants. However, in winter the uptake of pollutants by plants are minimal. Thus, the type of tree chosen depends on which problem of air quality you want to diminish.

In principal green roofs should influence the flow at the street level of an urban canyon less than green planted on street level, because the concentration of the pollutants is lower. Yang et al. (2008) used a dry deposition model to quantify the effect of green roofs on the air quality in Chicago (United States of America). They found that the annual removal of pollutants for Chicago was 85 kg ha⁻¹ yr⁻¹. Also the efficiency of green roofs to remove pollutants is low; it is still higher than what can be expected from bitumen roofs.

- Hesterberg, R., Blatter, A., Fahrni, M., Rosset, M., Neftel, A., Eugster, W., & Wanner, H. (1996). Deposition of nitrogen-containing compounds to extensively managed grassland in central Switzerland. *Environmental Pollution*, 91(1), 21–34.

- Nowak, D., Crane, D., & Stevens, J. (2006). Air pollution removal by urban trees and shrubs in the United States. *Urban Forestry & Urban Greening*, 4(3-4), 115–123.
<http://doi.org/10.1016/j.ufug.2006.01.007>
- Pugh, T. A. M., Mackenzie, A. R., Whyatt, J. D., & Hewitt, C. N. (2012). Effectiveness of green infrastructure for improvement of air quality in urban street canyons. *Environmental Science & Technology*, 46(14), 7692–7699. <http://doi.org/10.1021/es300826w>
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- Yang, J., Yu, Q., & Gong, P. (2008). Quantifying air pollution removal by green roofs in Chicago. *Atmospheric Environment*, 42(31), 7266–7273. <http://doi.org/10.1016/j.atmosenv.2008.07.003>
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4.4 Constructive requirements for rooftop adjustments

Not every roof can be adjusted to a green roof. The roof construction and the carrying capacity determine the possibilities for the construction of green roofs. The construction must be able to carry the green roof, but next to it, it must also be able to carry extra weight from for example people walking on the roof, water storage in the soil or snow. The lightest green roofs are extensive green roofs with mosses. These roofs have a substrate thickness from 20-50mm and have a weight from 10-20kg/m². On extensive green roofs with a substrate thickness from 40-150mm. not only mosses, but also, herbaceous vegetation will grow. The weight will be between 45-150 kg/m². Intensive green roofs have a substrate thickness from at least 120mm and a weight from 100 kg/m², but the weight can be even 750 kg/m² or more.

There are more things to take into account. For example, a proper draining system is required and the green roof has to be wind proof. In order to regulate the variety of green roofs systems and manage possible risks, SBR made a green roof directive called “Dakbegroeiingsrichtlijn”. This is a directive for planning, building and maintaining green roofs. The German green roof directive was used as a guidance as in Germany they acquired decades of experience with green roof directives. Among others, there are requirements for the building (for example carrying capacity), the used materials, the green roof (structure) and the vegetation (Losken, 2006).

- Losken, G. 2006. Dakbegroeiingsrichtlijn. Richtlijn voor ontwerp, aanleg en onderhoud van dakbegroeiingen. ISBN 978-90-5367-416-1

4.5 Technology description: readily available Breakthrough technologies supporting circular and climate-proof objectives

4.5.1 Bio-based materials in buildings

The use of renewable and sustainable building materials is largely growing. Advantages such as material efficiency, lower dependency of fossil resources and the focus of Life Cycle Assessments are giving biobased materials an important role in building innovation. Additionally, the lower environmental impact and the relatively small carbon footprint are making the use of biobased materials in the building industry important for reaching sustainability goals. The carbon footprint of biobased materials are relatively lower compared to fossil and chemical based materials (REF Dam, J. van and Oever, Martien van den, Catalogus biobased bouwmaterialen; het groene bouwen, ISBN 978-94-6173-3351, Propress, Wageningen, 2012) Biobased materials are relatively easier to be reused or recycled.

In the publication from Dam, J. van and Oever, Martien van den, Catalogus biobased bouwmaterialen; het groene bouwen is given a large overview of current biobased building materials and implementation challenges. Here it is stated that due to the rigid building sector and the lack of regulations on building materials the implementation of biobased and renewable materials is relatively low. However, it must be mentioned that users and project developers are increasing the demand for more healthier and sustainable building solutions.

Examples of this can be found in sustainable certification methods that are highly successful in the real estate market. On building and land use scale, points and certificates can be gained by scoring systems such as BREEAM and LEED. Points can be scores by using sustainable materials and circular design solutions. Branding and creating corporate social responsibility are drivers for developers to identify with these certificates.

Material certification example is cradle to cradle certification (<http://www.c2ccertified.org/>). Not only the cradle to cradle aspects of the materials are certified, but also the health impact such as radiation and toxic material use. This certification program is scoring on material health, material reutilization, renewable energy and carbon management. It is known that large prominent companies such as Google are creating their own healthy and circular material database for their project developers.

4.5.2 Circular building

Park 20|20 in Hoofddorp is a project development example where the focus is entirely based on circular economy. In construction of the building, building use and spatial development, Turn2 is another concept for circular building products, based on the principle that products are not sold to building owners, but the function of the product is leased for the period of use, and then after use, the product is returned to the producer. In chapter 3, more information can be found on circular building materials.

4.6 Considerations regarding investment

When opting for a readily available, or possibly a break-through, rooftop adjustment, several factors have to be taken into account when acquiring a clear picture before deciding on an investment. These factors are requirements for the building and rooftop construction, an overview of all potential (co-)benefits and side effects of the new roof, costs of the adjustment, the natural investment cycle and possible risks.

4.6.1 Developingg a business model

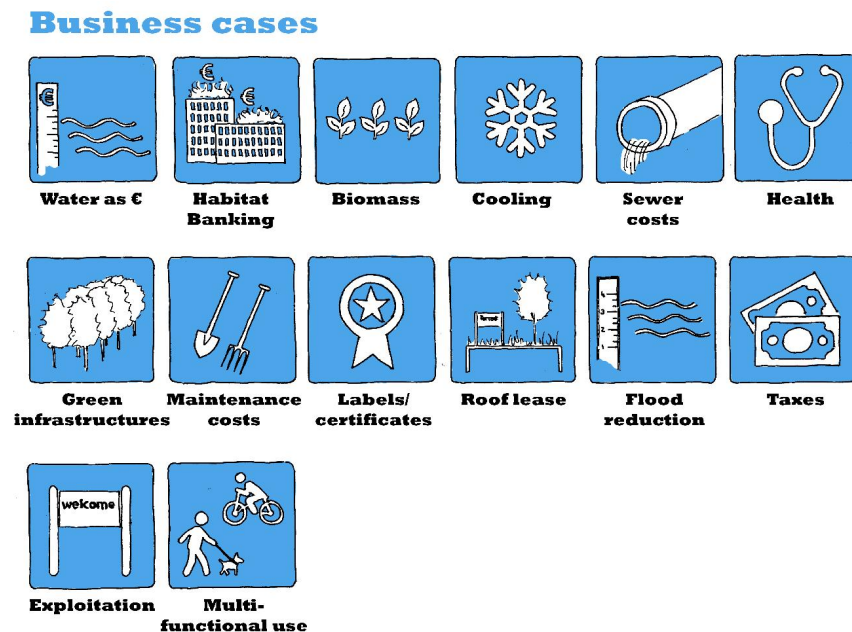


Figure 4.4 Possible business cases that enhance the development of green roofs.

The benefits of green roofs are, in contrast to energy roofs, not directly linked to the investor of the roof system. Benefits such as improved air quality and water buffering are social benefits and the responsibility of water management is directed by public institutes.

This means that, in order to increase the amount of Green roofs, challenging business model are required. However, by increasing the multifunctional use of roofs, roofs can become more than just shelter.

In San Francisco, with serious water shortage in summer periods and water overload by heavy rainfalls, interesting business models are developed for real estate owners. Buildings are getting an additional function as water storages with integrated water filtering systems. Water is becoming a serious business opportunity due to scarcity. This decentralized water system is stimulated by the government with special funding opportunities. Not only hidden technical water storage systems and purification systems can be found here in office buildings, but also indoor wetlands for water buffering and purification is an option. This will increase the value of indoor quality, by creating green spaces (REF biophilic design).

In the Netherlands with heavy rainfall and flooding risks, decentralized water buffering and storage can be also determined as a successful business model. When the flood reduction will become more of a responsibility for the entire society instead of a governmental issue, this will enable new solutions of water management. Especially buildings with large roof areas will have a large impact. Business solutions such as lowering of insurance fee, sewage tax or water board taxes are parameters that can have a positive impact on the increase of the amount of green and blue roofs.



Figure 4.5 Heavy rainfall July 2014, Wageningen The Netherlands.

Habitat banking

Habitat banking is banking with ecosystem services. This investment method gives the developer the possibility to create economic value to environmental benefits when restoring the local ecosystem. Green roofs can be used for habitat banking solutions. When building owners rent their roof for beneficial partners, this can create business opportunities. Green has been proven to have a positive effect on the health of citizens. Health insurance companies do benefit from a vital and healthy living environment. Renting of roofs may contribute to maintaining low health costs (research Witteveen+ Bos)

Social responsible investment

Green roofs can deliver a positive impact on the realization of Green infrastructures. Green infrastructures are crucial for the preservation of ecosystems. However due to urbanization and large building sizes, realizing green infrastructures on solid ground are not realistic. Especially for airborne species, green roofs can improve the local biodiversity. Green roofs can be an addition to existing green parks and areas, and enhance the urban green infrastructure.

Labels

In order to acquire a more founded application of sustainable rooftop solutions, scoring in existing sustainable labels is an important tool. According to the quick scan analyses of Platform BEE, a total of 1.4% of the BREEAM score of BREEAM in use can be appointed to a biodiversity roof. However, it should be mentioned that the BREEAM score is always a combination of building solutions, and cannot be seen as one solution.

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Multifunctional roof use

Multifunctional



When combining the green roofs with other solutions, this will create business opportunities and increases the value of green roofs. Multifunctional use of roofs will expand the function of shelter to opportunities of roof use such as recreation, restaurants or energy roofs. As rain falls on large roof surfaces and will be distributed to sewages, one could think about energy solutions of water energy in rain pipes. Additionally, the water on roofs can be used for indoor wetland, as is discussed before. Another advantage of green roofs is the decrease of maintenance costs, in comparison with bitumen roofs.

Combining a green roof with electricity production by solar panels results in a triple win-win-win situation: 1) green for biodiversity, improved air quality and water retention; 2), renewable electricity production; and 3), enhanced performance of the solar panels due to cooler roofs. Vegetation on roofs reduces the ambient temperature through evaporative cooling, thereby preventing the decrease in efficiency of solar panels with higher air temperatures.



Figure 4.6 Green energy roof (source: Barry de Vries)

4.7 Discussion

The rooftop impact model is a first step towards the validation of the impact of green roofs. It should be mentioned that there is a lot of information, but that specific research is required on the impact on roofs. For example, information can be found on the relation between vegetation and biodiversity; however this data is acquired on ground level, and not specifically analysed on roof and in the urban context. The data can give a guideline of the effects, however additional analysis is required.

As the data and knowledge is fragmented and the required expertise is quite broad, it can be suggested that with an open source system, the information can grow exponentially. A living document where everybody can add the required information will be suitable for the development of the rooftop impact model.

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(<http://www.groenegrondstoffen.nl/downloads/Boekjes/15Catalogusbiobasedbouwmaterialen.pdf>)
- <http://www.c2ccertified.org/>

5 Field lab Buiksloterham, Amsterdam

5.1 Description

Buiksloterham is a former industrial area, north of Amsterdam. In the area - which is still partially industrial, largely empty and partly polluted - will soon realize some 3,500 homes and 200,000 m² of space over the next 20 years (first buildings are already built). The (re)development is done by public and private parties, and there are high ambitions with respect to circularity. These public and private parties have signed a letter of intent in spring 2015 that stated the ambitions and vision for Buiksloterham.

The following goals for Buiksloterham are formulated:

- Buiksloterham is self-sufficient in energy and based on renewable energy
- Buiksloterham is a 'zero waste' neighborhood with a closed material flow as much as possible
- Buiksloterham is rainproof and gaining nutrients from wastewater
- Ecosystems are regenerated in Buiksloterham and natural capital is self-renewing
- Infrastructure in Buiksloterham is utilized to a functional maximum. The local mobility is 'zero emission' and, therefore, does not cause harmful emissions
- Buiksloterham is a diverse, viable and inclusive community
- Buiksloterham contributes to the local economy and is stimulating entrepreneurship
- Buiksloterham involves residents and businesses in local investment and value creation
- Buiksloterham is a healthy, safe and attractive area with space for recreation and relaxation

These goals and vision for Buiksloterham are based on a study/ analysis of the urban metabolism for Buiksloterham, commissioned and executed by organizations that are all active in Buiksloterham. Through the organization of 'tables' and 'meet-ups' on certain topics, such as energy, waste and water, stakeholders are involved to cooperate on the goals for Buiksloterham. The (re)development process has a highly voluntary character.



Figure 5.1 Buiksloterham on the map of Amsterdam (source: Visie en Ambitie Circulair Buiksloterham)

The first buildings in the area are designed and built by 'self-builders' that did construct their own house. Some of them did reuse (left over) building materials from other building projects. Housing Cooperation Alliantie will start building City plot: 500 residential buildings. Alliantie does have an ambition for new sanitation; separating gray and black waste water, where Waternet will process these water flows in a circular way (recovery of nutrients and energy). Looking at material use, Cityplot will be built in a rather traditional way (both material use for buildings and for public spaces). One of the reasons is also that the housing cooperation needs approval of their plans for the public spaces from the local Authority, and despite the ambition of policy makers in Amsterdam, the plan is approved under the 'puccini-method' that subscribes certain elements for public spaces in Amsterdam .

5.2 Use of Adaptive circular city knowledge for Buiksloterham

5.2.1 Relevant knowledge

Buiksloterham does not have the typical poor soil issues as described in chapter 2. The ambition on circularity and water is taken in WP of the ACC project. For this work package circular building materials and rooftop solutions are most relevant.

5.2.2 Organisation and stakeholder involvement

On the topic of 'waste' there are meet-ups with the local stakeholders. Here the process of stakeholder involvement is in its early stages. Architects are involved, and the first builders will be involved as well, however suppliers of building materials are not yet involved. There is ambition to re-use building components of a renovation project in Amsterdam of housing cooperation 'Ymere'. Further there is ambition to establish an agenda for the area that lists the practical possibilities/ needs for circular building in Buiksloterham. Again this process has a voluntary character with a strong focus on organizations that are already active in the area.

On the level of the city of Amsterdam there is a green deal cirkelstad. A few parties have already committed to this initiative, among them the authority of Amsterdam, two contractors and a concrete supplier. More stakeholders are to be involved. The scope of this green deal is both buildings and public spaces.

On building design there are requests for sustainable designs. There are all kinds of varieties of sustainability already build, and to be built in the future, resulting in several roof top solutions.

5.2.3 Comparing alternatives: results and recommendations

As both initiatives (Cirkelstad and Buiksloterham) are in the early stage of stakeholder involvement, the timing of these initiatives did not match the ACC project ambition to compare breakthrough technologies on their impact for the case study areas. From other projects it is known that circular building options can have potential to decrease environmental impact (CO2 and resource consumption and MKI), can be cheaper (as waste handling costs are avoided as well as costs for primary materials) and can be ecologically safe. However, there are also circular building options that have the opposite impact when compared to state of the art building options. For example, in Kringbouw (2003-2008) the energy consumption of several separation techniques appeared to be so high that CO2 emissions increased and costs. However, there is still technological potential for improvement, as well as replacement by other techniques, and therefore it is recommended to innovate for building projects with circular ambitions – and to support these innovations with the assessment of impacts, to stimulate product/ and technology development in the most sustainable direction (costs and environmental impact).

There is a similar mismatch in timing for the application of the rooftop model. Either designs are already made, and the building is built, or soon to be started, or the development is still that far away, that is too early to start thinking of the potential added value of rooftop solutions

6 Field lab Almere, towards a business proposition

6.1 Subsurface issues

Flevoland is an area in the Netherlands that has been reclaimed from the sea, see Figure 6.1. During the 20th century various construction works have been performed to accomplish this achievement. The works finished in 1968 with the most Southern part. Within ACC, in this region (indicated with the white circle in Figure 6.1) Almere is analyzed.



Figure 6.1 Flevoland. The region in the circle is the last reclaimed polder. The urban developments are also shown.

The subsoil is characterized by a shallow soft layer of intermittent eroded peat sediment, which geomechanically shows weaker than intact peat behavior. This material is underlain and overlain by soft clay layers. A dense Pleistocene sand layer forms a firm foundation base. Typical cross sections are shown in Figure 6.2. Note that the soft layer is about 5-6 m thick. After reclamation, the surface subsided rapidly

and in agricultural land is still subsiding steadily, according to the benchmark measurements shown in (Figure 6.3). Total subsidence already amounts to 1.9 m in about 40 years. In developed land where, as the standard method of preparation consisted of preloading with a sand surcharge of 1-2m, the subsidence was overprinted by a large settlement. Here the rate of subsidence has decreased and is leveling off, albeit slowly. This is shown by the measurements made by the radar satellites.



Figure 6.2 Geological profile through Almere.

In this area buildings in this region are mostly founded on the Pleistocene sand layers. Hence, they are not sensitive to shallow compaction. Therefore, an InSAR analysis was performed to separate measurement points at buildings from those at ground level. The results are shown in Figure 6.4. From this figure and Figure 6.5 it can be deduced that the presence of peat in the subsoil plays an important part in the localization of the areas prone to subsidence.

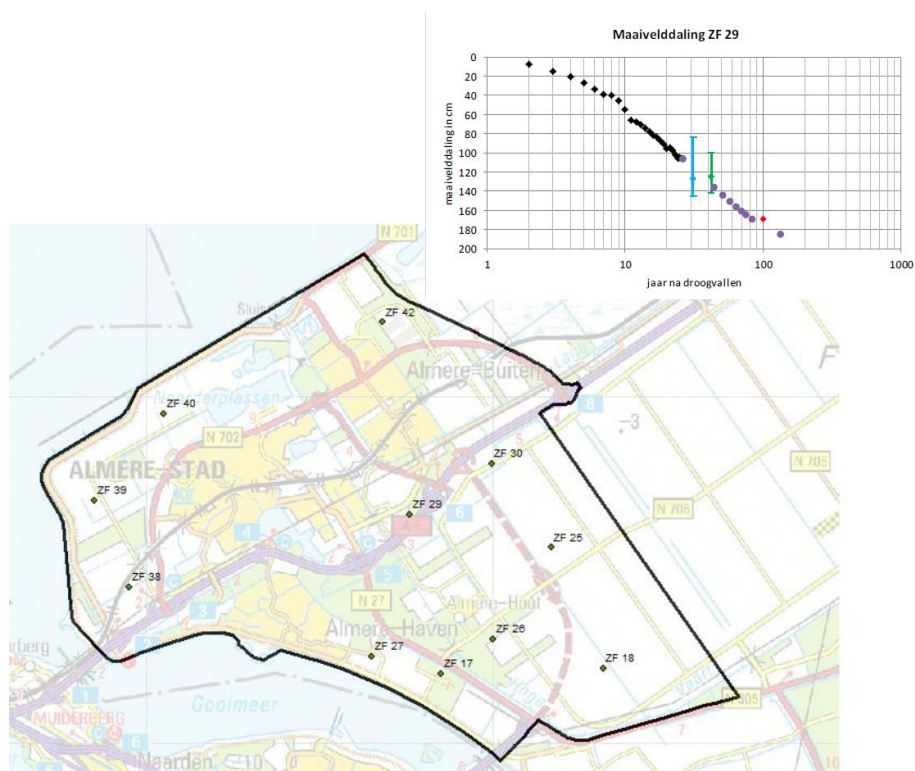


Figure 6.3 Subsidence of a benchmark in undeveloped land.

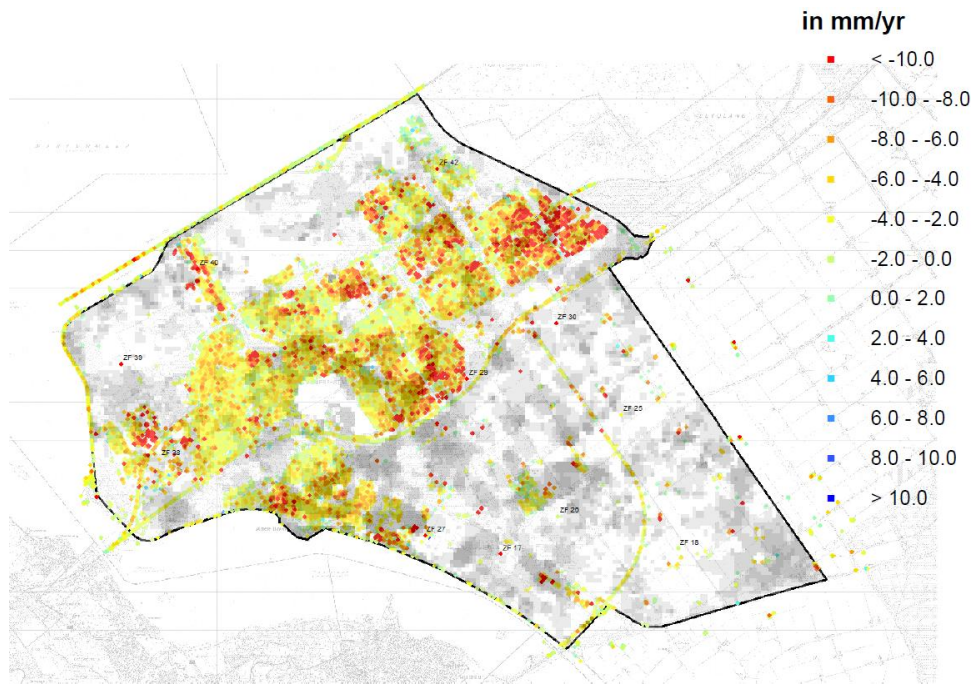


Figure 6.4 Measured InSAR subsidence rate overlain over the peat areas (darker grey) determined from the geological model NL3D of the Geological Survey of the Netherlands-TNO, available online.

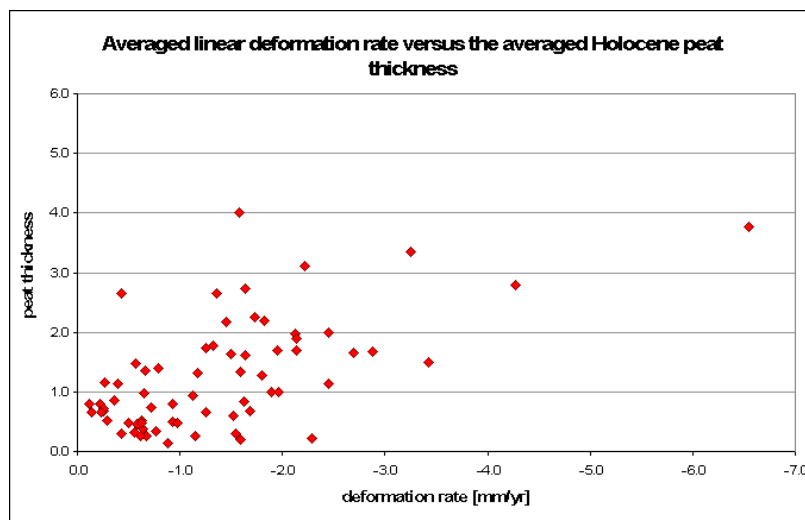


Figure 6.5 Cumulative Holocene peat thickness (top) and the linear deformation rates plotted against the cumulative Holocene peat thickness

6.2 Matching soft soil conditions, maintenance and management alternatives

Within the project Circular Cities, a study was carried out by means of a literature review and a workshop in order to investigate the possibility to best deal with the negative effects of subsidence within the contours of the planned maintenance and development of the public area containing both above ground and underground infrastructure in Almere (Figure 6.6). The workshop was held with representatives of the

departments of public works and development planning. The underlying motive was to make a transition from conventional preloading methods to create new developments, leading to damage to infrastructure and short life cycles, towards more sustainable and resilient methods in line with the “Almere principles” adopted by the municipality.

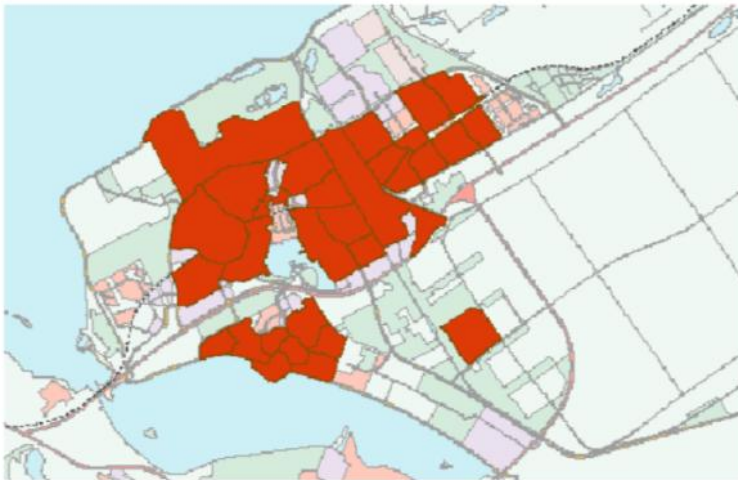


Figure 6.6 Areas designated for major maintenance (red) and development (pink) between 2010 and 2030

The workshop covered three main areas:

- Identify problems and how they develop them over time (Figure 6.8). A distinction was made between underground and surface infrastructure problems and issues between public and private space. Also a distinction was made which aspects of the soft soil problems are specific for Almere and which are generic.
- Identification and discussion of available techniques such as those already used in other soft soil areas. In addition, the usefulness of the different techniques for Almere.
- Identification of possible perspectives for future maintenance management, with attention paid to a public or private approach to the problem, including identification of possible stakeholders.

6.3 Conclusions and Recommendations from the workshop

The workshop led to an improved understanding of the problems caused by subsidence. The review of available methods and techniques led to insight which ones could lead to savings in maintenance and increased life cycles.

It emerged that the need for limiting the effects of subsidence is largest in the public domain, where differential settlements play a dominant role. These arise where underpinned structures (buildings, culverts) are connected to non-underpinned structures (conduits, pavements) and also arise as a result of a heterogeneous soil structure. Moreover, it was found that actually occurring settlements are (much) bigger and longer-lasting than was inferred from previous forecasts.

Recommendation: to determine the limits within which the subsidence will develop in the and how alternative management and maintenance techniques and strategies can help to increase the efficiency of maintenance and life cycles.

Favorable conditions for Almere are the quality foundations (concrete piles) and the fact that groundwater management is aimed to keep the peat layers as wet as possible.

Unfavorable for Almere is the large area of building sites that are already owned by the municipality, but still cannot be developed, owing to the economic situation. This puts a huge financial burden on the municipality. Also unfavorable is the change in the policy that the duration of surcharge has been changed from 4 years to 3 years, which leaves still potential for continued settlement.

During the preparation of the new developments a number of improvements can be made which result in future savings in maintenance such as:

- The minimization of the residual settlement and monitoring this during the preload surcharge period.
- Accelerating consolidation of the soil. Here some measures should be considered such as:
 - o The removal of peat layers and possibly also clay layers prior to adding surcharge sand.
 - o longer preload periods.
 - o The use of temporary overload.
 - o The use of vertical drainage in order to speed up the consolidation process.
 - o Taking the soil structure into account when planning the layout of the development (Figure 6.7.

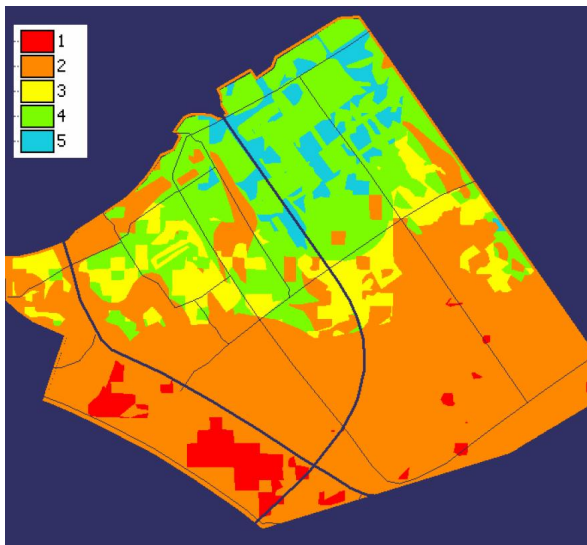


Figure 6.7 Possible suitability map based on the geology in Almere for the water and green function (1 = very bad, 2 = bad, 3 = moderate, 4 = good, 5 = very good)

Recommendation: selection through an analysis (eg SWOT) of the most efficient method of surcharging strategy in Almere; mind that shortening the preloading period from 4 to 3 years will lead to higher maintenance costs in the future if no consolidation accelerating measures are taken.

In addition measures may be taken in order to delay the settlement process - for example, in repair and reconstruction, such as through the use of lightweight materials and through the use of innovative techniques at transition areas.

Inspection of the results of monitoring can reveal differences in subsidence. Interpretation can help in reducing differential settlement during future upgrading and / or maintenance. Monitoring can also contribute to the improvement of maintenance and reconstruction plans.

ARCHITECTURAL DETAILS

heightening
sewerage
housing
drainage

streets are heightened with sand
main roads + sewerage are piled
houses are piled

main roads + sewerage are piled
houses are piled

street is heightened with sand instead of excavated material

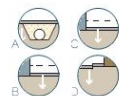
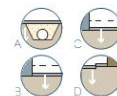
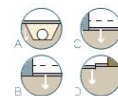
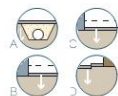
main roads + sewerage are piled
houses are piled
block drainage

only main roads are piled
block drainage

citizen's responsibility
only main roads are piled
houses are piled
block drainage

DAMAGES AND EFFECTS

A. sewerage
B. housing
C. garden
D. public space
E. district heating



POLICY OF MAINTENANCE

surface water level
de-watering
urban planning
pre-loading
heightening
maintenance
urban planning

excavated materials in-situ re-used for heightening
subsoil not seen as part of urban planning

administrative attention for maintenance

major maintenance every 15-20 years

limited period of pre-loading
major maintenance every 15-20 years (replace all pipes from GREX to BGRIEX)

keep surface water level at -6.20m
pumped drainage
policy of water management related to land subsidence
piles of sand used for pre-loading
all materials in-situ re-used for heightening
subsurface is included

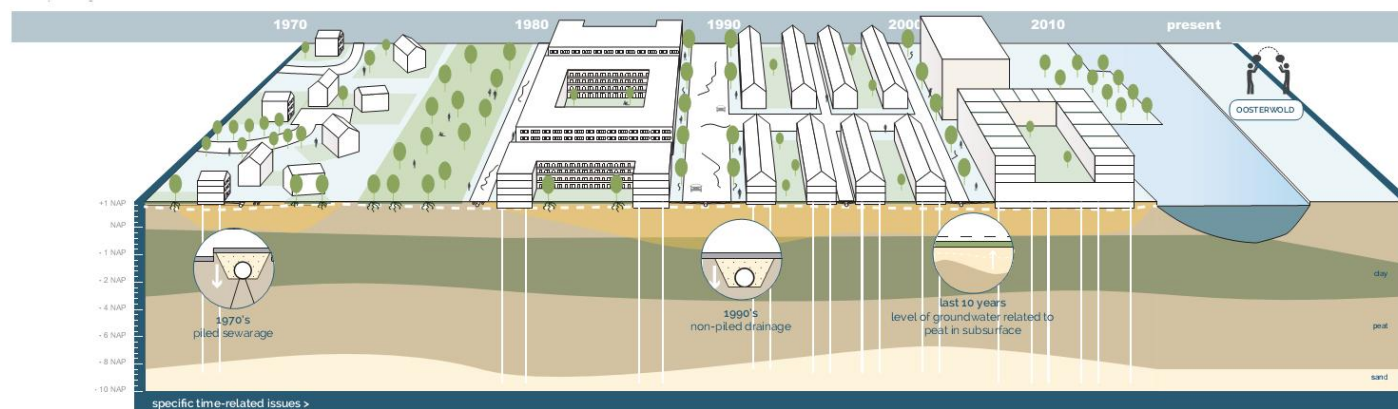


Figure 6.8 Viewgraph of the development of the city of Almere, showing the problems encountered over time.

Such measures can only be taken in close cooperation between the different departments within the Municipality of Almere. Our study showed that at the moment optimization of the maintenance process takes place at the service level only. This hampers an optimal result for the whole of development and maintenance activities. By including wider interest groups such as those of residents and businesses, the water board, the province and subsoil infrastructure operators, a broader societal cause is served.

Recommendations: *To obtain a more detailed understanding of the costs associated with subsidence
Pursue a policy (action perspective) based on the optimization of societal costs and benefits*

To achieve the latter it is recommended to achieve greater agreement among –at first - all the relevant municipal services, and - at a later stage - with all the stakeholders involved (Figure 6.9).

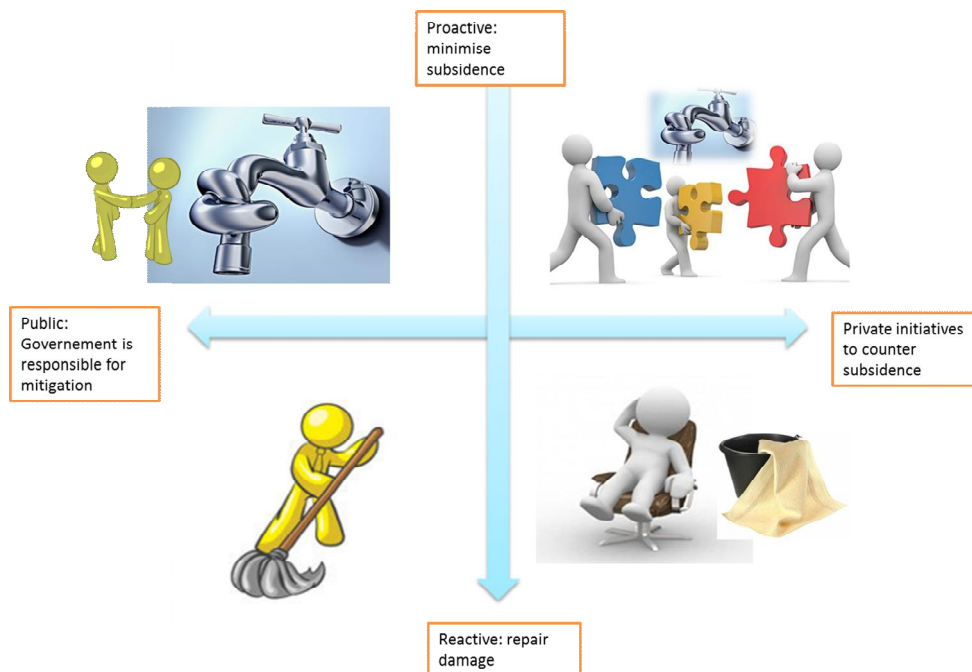


Figure 6.9 Viewgraph showing the different approaches to counteract subsidence effects from the viewpoint of the stakeholders

When it is planned to involve the private sector closer in the management and maintenance of public space it is needed to formulate requirements that must be met. In this area, little experience is as yet available.

Recommendations: *If the municipality is considering diverting more responsibilities to the private sector terms of management and maintenance, close attention should be given to the formulation of the requirements and boundary conditions.*

A multi-year plan for maintenance and management is part of a maintenance strategy. This planning is based on forecasts. Forecasts are only exact within a certain range. Moreover, deviations occur due to external changes, such as groundwater levels, changing climate and the like. It is therefore important to regularly review the long-term prognosis with measurements.

Recommendation: *To design a monitoring strategy on the basis of goals which have to be formulated first*

The problems associated with the occurrence of soft soil and land subsidence occur in many municipalities in the Netherlands. Some of these municipalities work together and exchange mutual knowledge and experiences. Although Almere has some specific characteristics, there are also some things that are similar to the problems of the other soft soil municipalities.

Recommendation: Engage in cooperation and knowledge exchange with other soft soil municipalities. Try to initiate a research program to answer generic problems

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6.4 Floriade: First building

In 2022 Almere will host the Floriade, the World Expo on Horticulture. This year the design is made for the first building (the so called innovatiewerkplaats) by Architect Duzan Doepel of Doepel Strijkers architects. The building will be built next year in 2016. It will be used for educational and research purposes and will be further developed over time for the Floriade expo along with the surrounding area.

The design of Architect Doepel Strijkers tells the story of Flevoland. Where there was only water in the past, there is now a unique area which is on average five meters below sea level (NAP). A 5 meter thick layer Flevoland bottom is lifted to the NAP-line. The facade of the ground floor is an outside mirror. The environment is reflected in the mirror, thus creating the image of floatation. The major height levels of Flevoland are visible in the pavilion. The roof is used to grow crops in Flevoland and symbolizes the fertile land in Flevoland.

In November a workshop was organised with Duzan Doepel to brainstorm on possibilities to integrate knowledge from this project in the further design / development of the building. The options will be further explored in the future.



7 Conclusions and recommendations

7.1 Recommendations for knowledge integration in building investment decisions

The project had the scope of 1 year time, start January, end December, with the ambition to support actual 'cases', development projects with the combined knowledge of Alterra, Deltares, ECN and TNO. However this predefined timeframe did not well match the timeline in the cases, or investment opportunities. Sometimes, crucial decisions were already taken, for instance by Housing cooperation the Alliantie for Buiksloterham. The design for 800 houses was already made, permits were ready and the building of the houses has to start soon in 2016. In other cases, the process was too premature to introduce models for the assessment of the societal impact of investments, for instance in Amsterdam regarding the green deal for circular buildings. As the timeframe of investments has to be leading for decision making, there needs to be flexibility in time to add the relevant knowledge. This flexibility was lacking in this project.

Another experience is that it takes time to understand the questions related to investment decisions, as well as for the investors to understand what knowledge is available to be used in the decision making process. It is recommended to continue to build on the network of investors, the related stakeholders in the building chain and knowledge institutes.

In WP1 a more elaborate evaluation is made on the lessons learned regarding integration of knowledge in city development.

7.2 Adaptive Circular City project: combining knowledge

The projectteam members did not know each other before the start of the project, or where they familiar with the each other's background knowledge. As to be expected with multidisciplinary project teams, it took some time to get familiar with the approaches. Although this is not the first multidisciplinary work, lessons learned on multidisciplinary work are also applicable on this project. More information on multidisciplinary work can be found in the report delivered by WP1.

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