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Industry and infrastructure under green roof – different backgrounds, various solutions

Known since ancient times, roofs deliberately covered with plants are currently growing in popularity in highly developed countries.

The most intense research and technical experience gathering in green roofs takes place in Germany since the beginning of 80. in 20th century. In that country 25 million m^2 of green roofs were installed between 2000 and 2001 [7, p. 17]. Such development is the effect of the state policy. The municipalities of over 250 German cities and towns promote green roofs through various direct and indirect incentives. Many cities in other countries do the same, i.e. Linz in Austria, Basel in Switzerland, Ontario in Canada or also Beijing in China. In those places green roofs gradually become an important part of the urban cityscape. On the other hand in places where legal incentives do not exist green roofs are still rare. Some cities, eg. London, are now seeking to settle their own policies and regulations to promote green roofs in a way that would suit them best, i.e. best solve their specific problems. This tendency reveals that green roofs are treated as an efficient tool towards implementation of sustainable development in architecture [18].

Statistics for Great Britain claim, that building construction and maintenance is responsible for 48–50% of the country's total CO_2 emissions. As increasing emission of green-house gases, mainly CO_2, is regarded as the main reason behind global warming, the target of radical reduction of architecture's carbon footprint is gradually included in the policies of developed countries. CO_2 emission is mainly a by-product of building materials production, transport, construction process and interior microclimate control relaying mainly on fossil fuels. Increased presence of CO_2 in the atmosphere is also a result of forests' cutting and general decrease of green areas that absorb carbon dioxide and produce oxygen. Green buildings assessment systems like British BREEAM or American LEED concentrate on these issues [2]. Such assessment methods do not mention the green roof as a suggested solution for environmentally conscious design, nevertheless advantages that green roofs bring are highly scored [6, p. 34]. Apart from the diminishing of the carbon footprint, sustainable water management and encouragement for urban biodiversity are regarded as key targets of sustainable architecture. Green roofs are considered to be beneficial to the environment in all the foregoing aspects. Their supporters thus emphasise their positive influence on water management, indoor and immediate surrounding microclimate control. They also indicate that green roofs increase urban biodiversity, absorb carbon dioxide and airborne particles and produce oxygen.

This paper analyses specific reasons for the introduction of green roofs onto industrial and infrastructure buildings. At the same time it presents broad lines of green roofs growing popularity in architecture.

Green roof typology

Two main types of green roofs are classified: intensive and extensive. Intensive green roof, depending on the soil depth, may support a wide variety of plants: grass, flowers, shrubs and even trees. The plants on such a roof require cultivation, watering and fertilization like those in traditional gardens. Intensive green roof is usually planned as a recreation and leisure area. It is thus an important design issue to assure its accessibility. The positive effect of such spaces on life quality in the cities and also on increase of prices of overlooking estates is broadly discussed in literature [13, p. 5]. It is even promoted to use roofs for local food production. Intensive greening, due to its substantial

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load and high maintenance costs, is rarely introduced onto large areas of production or infrastructure buildings. It can be admired however on the Drinking Water Purification Plant in Whitney, USA and Antorini Winery in Barginio, Italy, both described further in this paper.

Extensive roofs are lightweight due to the thin substrate depth – ranging from 5 to 12 cm. They are also designed for minimum maintenance requirements. It may be enough to perform rainwater inlets cleaning and general inspection once a year. The most common plants used for the extensive roof are drought resistant sedum and other succulents (Fig. 1). A popular proprietary system is a sedum matt. This solution has dominated the roofs of industrial halls.

Fig. 1. Sedum cover on extensive roof one year after planting (photo: Mark Depreeuw)

On-site benefits for the owner and off-site benefits for the public

Introduction of the green roof impacts not only the building it covers but also its near and more remote surroundings. This influence may be analysed in different scales: building and site, vicinity and surroundings and even regional – global. What's more the same feature may be valuable both to the building's owner and to the surrounding area, or close vicinity and wide region.

In the **scale of a building** an undoubted private benefit is the extended durability of properly applied water proofing membrane. In Germany, a country with the biggest experience in green roofs, the manufacturers of EPDM type membranes give about 10 years longer warranty for their product if covered with green roof layers. Germans have also developed detailed building standards governing material use, construction principles and maintenance requirements of green roofs [8], [9]. However in Great Britain, where green roofs are still an emerging market, the warranty for water proofing is the same no matter what it is covered with. Longer durability of water proofing membrane generally is an asset for the environment at a global scale: slower damage means postponing the necessity to exchange the material for a new one.

The green roof is regarded as an improvement in a building's fire protection. Due to its mass it is also a good acoustic insulation. The performance of sound insulation depends on the depth of the substrate and it's moisture content [6, p. 8]. This feature may be regarded as an asset in some locations, e.g. in the proximity of airports.

A green roof is generally regarded to be beneficial to the environment, among other reasons, through it's influence on the microclimate of the interiors it covers. A pinpoint study of this influence in a 'typical' commercial property was carried out by Joanna Facer in her undergraduate project at Cambridge University in 2005. She compared data concerning costs and benefits to the environment of various greening features (mainly energy consumption and carbon dioxide emission) in two theoretical commercial properties: one 'greened' with natural ventilation and the other one with air-conditioning and no vegetation. Conclusions of her report challenge the popular explanation of environmental benefits of the green roof. According to her calculations, in British climate, green roof is beneficial because it supports natural ventilation, which makes it possible to avoid expansive and energy consuming air-conditioning. In Britain, natural ventilation is efficient, with the exception of short terms in the summer, when it is difficult to avoid the building's overheating. And this is where a green roof can make the difference. Through shading, evapotranspiration of plants and thermal mass of substrate it substantially diminishes temperature of the layer beneath the soil. An exposed black roof surface on a cloudless summer day can reach 80°C, and a corresponding surface of roof covered with grass is only 27 °C. With expected 21 °C inside, the temperature difference on the roof drops from 59 °C to 6 °C which reduces the heat flow through the roof by 10 times [6, p. 26–27]. On the other hand thermal resistance of properly insulated roof (minimum thermal resistance for insulated roof according to Polish building regulations is U = 0,30 W/m²K) remains almost the same, no matter if the roof is greened or not. The positive difference greening brings in this respect can be easily reduced with a few millimeters of additional thermal insulation. And that means that the green roof does not contribute to winter heating savings. Facer concludes that the green roof that is not a part of a broader passive design solutions does not give the building's owner major benefits neither in energy consumption nor in CO_2 emission. It facilitates however effective natural ventilation and that leads to significant economic savings and environmental benefits. In this paper there are two examples of environmentally sound industrial architecture that incorporates various passive design solutions, and green roofs among them. These are Ecover factory and A&C in Belgium. Both were designed by architect Mark Depreeuw.

Another argument for beneficial results of combining green roof with other sustainable solutions in one design comes as a conclusion of German research on positive mutual influence of photovoltaic-panels installed on the green roof. The vegetation cover diminishes roof surface temperature which leads to higher efficiency of photovoltaics. What is more the shade that panels cast on vegetation protects it from overheating and drying. In result the extensive vegetation becomes more diverse and significantly higher [10, p. 152]. Energy produced by PV system is the so-called 'green energy' which does not contribute to CO_2 emission increase. Global (public) benefis of its production are thus clear. In Germany the operator of an energetic network is obliged to receive it and to pay a price that is higher than that of 'standard' energy. Thus positive interaction between PV panels and greened roof gives the owner economic benefits.

It is difficult to evaluate economic benefits for the owner resulting from aesthetic value and functional potencial of the green roof. The intensive ones are usually additional or even the only outdoor recreational space for the buildings occupants. This asset is particularly important in dense city centers.

In the scale of **vicinity and surroundings** one of the most valued features is the green roof's ability to retain 40–50% of annual precipitation that falls on them and also to slow stormwater runoff to sewage system [5]. What is more, vegetation and soil filter rain water thus it leaves the roof cleaner than that from, eg. bituminous surface roof. Rapid increase of water flow in the sewage system in case of a gusty rainfall is a serious problem for many urban areas where impervious surface dominates. Redundant water causes the sewer's replention and overflow which results in pollution of the rivers. Rapid runoff rate increases flood threat. These where key reasons for implementing active policy to encourage green roofs in one of the most flood prone cities in Europe – Cologne in Germany [14, p. 34–35]. In the case of large areas of industrial halls stormwater retention is an important benefit of green roofs. The quantity of retaind and filtered water for roofs covering many acres is substantial. Sustainable water management and the goal of keeping all the rain water on site was one of the drives for designing green roofs on the Ecover factory in France or Ford in Dearborn in USA.

Another important benefit in the scale of surroundings (and globally) linked with green roofs is their impact on moderation of urban heat island effect. The urban heat island effect is the difference of even a few degrees in tempeature between a city and the surrounding countryside. This phenomenon was described after long term observation of large urban areas. It leads to many negative results, eg. interference of the water cycle (more rapid evaporation, more frequent storms), increase of energy consumption for air-conditioning (which additionally increases the outside temperature) and increase of smog. In the proces of evapotranspiration plants can cool the cities: they absorb heat from their surroundings when evaporating water. The plants also partly reflect solar energy. The mitigation of urban heat island effect and sustainable water management can bring economic benefits, that are estimated by each city planning its own green roof policy. A factor that is much more difficult to calculate although regarded as a benefit in the scale of vicinity is the aesthetic potential of a green roof. Landscape visual protection is sometimes an important issue integrated in development regulations. When planning large industrial or infrastructure premises in protected landscape green roofs often becomes an

Fig. 2. Various vegetation on a brownroof over staff facilities building in syenite mine in Niemcza, Poland. The picture is taken a year after the soil from the surroundings was elevated onto the roof. No vegetation was planted (photo: M. Baborska-Narożny)

obvious solution. This was the case in Baumgartner factory in Hagendorn, Switzerland (arch. Graber & Steiger), Benkert in Alterhausen, Germany (arch. Mario Botta), Rolls Royce factory in Goodwood, England (arch. Nicholas Grimshaw) and water purification plant in Whitney, USA (arch. Steven Holl).

The benefit that can be analysed in **a regional-global scale** is lowering of the carbon footprint of built up areas covered with vegetation and also increase in biodiversity of urban areas. Biodiversity seems especially important in densely built environment of city centres. The research into this problem proved that green roofs can help sustain rare species of birds, insects and plants. Finding that as an important asset led to the invention in the last few years of the so-called brownroof that remains a similar eco-system as brownfield. Nature scientists found that urban brownfields became rich and diverse ecosystems that could be preserved even when they aquire a new function. It is enough to lift the crushed rubble from the site onto the roof and leave it to self colonise (Fig. 2). The seeds of various plants come with the rubble or with the wind. This method was used to cover newly built roofing over platforms of a Zurich railway station and Laban dance centre in London (the first roof of the kind, arch. Herzog & de Meuron, 2002). A different reason stands behind the same solution of brownroof over administration and staff building in a syenite mine in Niemcza, Poland.

The green roof is also regarded as a means of improving air quality. Planted roofs remove airborn particles, volatile organic compounds and heavy metals.

Selected case studies

Lake water filtration plant in Wollishofen in Zurich

Fig. 3. Entrance into water filtration plant in Wollishofen in Zurich, Switzerland, is restricted for the employees. The meadows on top of the horizontal historic buildings remain invisible for a passer-by (photo: K. Kościuk)

Fig. 4. The orchids on the roof meadows of Zurich Water filtration plant could not be better protected in a nature reserve (photo: K. Kościuk)

One of the most imposing and at the same time forruning green roofs over an infrastructure building can be found in **Wollishofen** in Zurich, **Switzerland** [12]. The continually functioning structure was built as a lake **water filtration plant** and covered with soil in 1914. The city encompasses the northern part of the reservoir, which covers 70% of communal water consumption. The green roof was implemented because of its cooling effect known even at that time. It was essential to prevent the water that was slowly filtered through a layer of sand inside the building from overheating. The 3 ha roof divided in four separate sections is covered with a meadow, that now consists of 175 species, including many plants that are rare or endangered. Special enthusiasm evokes around 6000 specimen of (lat.) *Orchis morio* extinct in the region of Zurich. The whole variety of plants brings back the richness of flora from the beginning of the 20th century. It came onto the roof either with the soil from the surrounding farmland that was lifted there or from the seeds blown with the wind. No plants were planted. The roof construction is ferroconcrete slab beams 8 cm thick, water proofed with 2 cm mastic ashalt. On top of that 5 cm of sand and gravel creates a drainage layer covered with 15–20 cm of soil. The two upper layers mixed with the passing of time, which did not result in any damage to impermeability of the roof. The specialists emphasise that since its construction there have been no technical defects like leaking that would require intervention. Until now the only reconstruction works carried out were at the edges. The roof divided into four separate parts rises about 4 m above the surrounding ground level. Public access to the roof is not possible. What is more it is not even visible for the passer-by (Figs. 3, 4). This botanic treasure is in direct vicinity of a motorway junction. There are propositions that Canton of Zurich should protect the vegetation on the roof.

The water filtration plant in Wollishofen proves that a large infrastructure building can successfully coexist with surrounding nature and even become it is important part.

Baumgartner window factory in Hagendorn, Switzerland

Similar expectations were formulated as a development regulation in the case of the Baumgartner window factory in Hagendorn, Switzerland [17]. The investor made enquiries with the authorities of the town Cham with the possibility to extend the existing factory with additional space of 18 000 m^2. Keeping the location of the factory in Hagendorn was essential since the company secures a majority of the jobs in the small village. Nevertheless this location was a source of serious debate since it lies in an agricultural zone of federally protection-worth landscapes (BLN). The resulting design is an effect of close co-operation between the investor, municipality representatives and designer, especially at the preliminary design stage. The municipality demanded an architectural competition, and obliged the owner to include the surrounding area into planning. Niklaus Graber and Christian Steiger from Luzern won the competition in 2001. They cooperated with landscape architect Stefan Koepfli. The planning that followed took almost five years. The construction was completed in 2006. According to the architects the structure functions as a hybrid of landscape and architecture [24]. The 18 000 m^2 roof is covered with a damp meadow. The roof is boldly cantilevered over the outside storage and delivery area. Such a meadow originally grew in this place, which is flood-land between the rivers Reuss and Lorze, before it was turned into a corn field. Like in the Zurich water filtration plant the local ground is lifted up onto the roof. In this case however the substrate mixture is elaborated, it consists in 50% of 15 cm of ground excavation from under the buildings' footprint and the rest is brick scrap. A special technical water system was developed to simulate natural conditions. A mock-up roof meadow was tested before the final construction was completed.

The horizontal meadow remains invisible from the ground level [22]. It plays a crucial role in the elimination of the need for production hall air-conditioning. What is apparent for a passer by is a wooden vertical structure that encompasses the whole building. This structure will be filled up with plants as they grow, creating a hedge reaching the roof hight.

Benkert bench factory in Alterhausen, Germany

The local development constraints were much the same as in Hanendornt and led to the inventive design of the Benkert factory in Alterhausen, Germany [3, p. 52–54]. The structure was built in 1996. The decision to green the roofs over two symmetrical production halls was an effect of close co-operation of the designer – architect Mario Botta, the investor and local authorities. The will to protect valuable landscape and unobstructed views was the starting point for the design. Location of the new development on top of the hill at some distance from the village was carefully selected. The architect proposed a building partially sank into the ground and covered with grass that continues on gentle slopes that reach the level of the surrounding terrain. In result the geometry of the hill remains almost unchanged and from some points of view the factory is difficult to notice at all. The factory design as well as whole production process integrates many environmentally friendly solutions. The green roof helps to keep the temperatures inside on a stable level.

Valuable landscape preservation and sustainable manufacturing principles were the main reasons behind the broad use of vegetation, including roofs, in **the Rolls-Royce factory in Goodwood** in southern England. The development designed by Nicholas Grimshaw opened in the year 2003. At that time it was the biggest green roof in the country, covering about 33 000 m^2. Among other public and private benefits, it proved to be a valuable habitat for many species of birds [4].

Similarly green roofs conceal a beautifully located **Antinori Winery in Barginio**, near Firenze, Italy. For over 600 years the Antinori family has been involved in wine making and their properties are continuously expanding. Their new development was designed by Marco Casamonti from Archea Associati in 2005 [15]. The construction is due to be finished by the end of 2008. The building is intended to go beyond its fundamental function, i.e. wine production, and is supposed to serve as a main attraction point of the region for enoturism enthusiasts (clients of tour services related to wine product). One hundred thousand visitors are expected annually. What's more a kindergarten, bakery, library, workshop and some shops are also included in the program. Such a rich public offer was ment to be contained in the form that best expresses the culture of wine making. Among other means selected by the architect to achieve this goal intensive green roofs are the most striking and appealing feature. The whole structure dug into the slope of a hill is covered with the vineyard. Planted on the hill it continues without any disturbance on top of the building. Two horizontal cuts and some skylights let the sunlight into the interiors. Conceptual coherence rather than sustainable design principles seem to be the reason for the implementation of green roofs in this case. In their description of the design the architects do not mention any potential environmental benefits resulting from the vegetation on the roofs [21].

Ecover ecological detergents and the cleansing agents factory in Oostmalle, Belgium

The green roof over the Ecover factory in Oostmalle, Belgium, was introduced without any suggestions or incentives from local planning authorities. So far there are very few towns in Belgium that actively promote green roofs. Ecover is a manufacturer of ecological detergents and cleansing agents who received numerous awards as a sustainable entreprise [23]. Its factory in Oostmalle opened in the year 1992 and is regarded as the first ecological factory in the world. It was designed by architect Mark Depreeuw who is devoted to sustainable design in all his work. Among many solutions that legitimize the 'green' label attached to its architecture, the Oostmalle factory is covered with an extensive green roof covering 6000 m^2. Initially the roof was designed to be vegetated with grass. This proved to be a bad solution however, as far as sustainability was concerned, because with a 15 degrees roof grade and only a few centimeters substrate depth the grass dried in the summer month and required watering. Watering the roof was regarded by both the architect and the client as contradictory to sustainable architecture principles. In the year 2005 necessary repairs of the EDPM membrane were conducted and the whole vegetation layer was exchanged for a substrate covered with sedum. So far it functions without any further problems (Figs 5, 6).

Fig. 5. Entrance to Ecover factory in Oostmalle, Belgium. Sedum on the slightly pitched roof of the production hall is visible from the surroundings (photo: M. Depreeuw)

In the year 2007 Ecover opened another ecological factory in Boulogne-sur-Mer, France. The development is located in a newly established business park, Parc Paysager d'Activités de Landacres. The Landacres park is the first of this kind in Europe to have achieved the ISO 14001 certificate for environmental management. It is claimed that only enterprises doing business in a sustainable way can invest there. The first concept sketches were done by Mark Depreeuw. The whole project and construction of the building with a surface area of 11 300 m^2 was commissioned to the Japanese corporation Takenaka. The factory building process lasted since June 2006 until April 2007. Part of the building is two stories high. The extensive green roof covers 8000 m^2. The designers emphasise that the vegetated area of the roof is almost the same as the buildings footprint. In opposition to the above mentioned conclusions of Joanna Facer's research, the Takenaka architects claim, that the green roof not only minimises the need for interior summer cooling but also due to its insulation qualities helps cut the energy use for winter heating. Among other benefits of the green roof they outline rain water retention. The remaining volume of water that flows down the drain is caught into two containers 10 000 l each and after filtering it is used as grey water for toilet flushing. Numerous other design decisions were made with the aim to diminish the buildings environmental impact, eg. in the material selection process the basic criteria was whether it is recyclable, produced with the least amount of energy and with minimum environmental contamination from renewable raw material. Thus it was decided to avoid steel and aluminium and to maximise the use of wood and concreate [27].

In both Ecover factories the construction of the green roof was the result of the enterprise's own standards and expectations towards architecture. Buildings are regarded as an integral element of the company's consistent profile of sustainable, ecologically sound business.

Fig. 6. General view of Ecover factory in Oostmalle. The picture shows grass on the roof which was later exchanged for sedum (photo: archive of Mark Depreeuw)

Selected American buildings:

Water purification plant in Whitney, Connecticut, USA

Untill recently green roofs have been voluntary in the private sector in the USA [26]. The implemented green roof policies in, eg. Chicago, Portland or Toronto apply to public developments or receiving public assistance. Expected private benefit of the ower is the main incentive to install a green roof. Investing in the instruments of green architecture in industrial developments is often assumed helpful in building a coherent, economically driven identity of a sustainable business. The growing number of industrial premises applying for a voluntary environmental performance assesment, the so-called LEED, is an illustration of the trend [2]. What is more in some cases, notably with large infrastructure or industrial buildings, winning favourable opinion of local inhabitants may have influence on the location of a development and the whole process of gaining a building permit. Using green architecture tools, among others also green roofs, seems to be an effective method.

Such was the background of the design process of the water purification plant in Whitney, New Heaven in Connecticut, USA. The development at the early programming stage was ment to become an important element and attraction of East Rock municipal park. The site is within a picturesque protected landscape. The investor, South Central Connecticut Regional Water Authority expected protests from local inhabitants against plans to build in their vicinity a water purification plant that would serve the needs of half of the state. What is worse the technically ideal site happend to be an attractive green public leisure spot. Anticipating protests the investor assigned the project to a star architect Steven Holl. A spectacular green design was developed. Green features include sustainable material choice, water management, creation of diverse ecosystems for migrating birds and the biggest green roof in the state [20]. The structure is merged into the surrounding landscape. The whole volume is partially sunk into the ground. The green roof plane smoothly continues in one direction to melt with the neighbouring hill. The proposed scheme turned the infrastructure building into a landscape feature and an educational facility with public access. The site, the green roof over the major volume and vertical greenery were designed by landscape architects Michael Van Valkenburgh Associates. The green roof became the main attraction of the building as an unusual educational space open to the public. The varied vegetation is planted on the roof in a way that metaphorically reflects and explains the technological processes going on underneath. In the background of the vegetation one extravagant longitudinal element is exposed. In a 110 m long form, covered with reflective stainless steel skin, technical spaces, laboratories, lecture rooms and conference facilities are located. The design gained full support of the local community and the building was completed in the year 2005. In 2007 it was granted the AIA COTE Top Ten Award [1].

Ford Motor Company River Rouge Plant, Dearborn, Michigan, USA

En example of a green roof functioning as a sign of sustainable manufacturing is the development of the Ford Motor Company in Dearborn, Michigan, USA.

The construction of a public observation tower with a view onto the vegetated roof was planned at the preliminary design stage. No public access to the extensive roof covering area of 40 000 m^2 was planned. The Ford's premises in Dearborn, where the new production halls are located, are the icon of American industry in the 20^{th} century [2]. It is a popular tourist point of interest. The decision of the company's shift towards sustainable manufacturing was to be illustrated with the revitalisation of the River Rouge brownfield. William McDonough a prominent architect among sustainable design advocates was assigned the whole revitalisation project. Various environment friendly features were thus included into the design. Some of them experimental. The green roof, completed in the year 2002, is one of the most visible ones. Most of the outlined above benefits of a vegetated roof, public and private, were taken into account. The architect and investor proudly announce that for a few years now the roof has been a nesting place of the Killdeer; a bird rarely seen in the region. In the year 2004 the development won the Green Roofs for Healthy Cities Award of Excellence in the Extensive Industrial Commercial category [25].

Conclusions

The insight into the green roof's impact on their surroundings, not only the direct vicinity (eg. through their water retaining quality they help prevent river contamination), well illustrates how complex are the effects and side-effects of building for the habitats. How single developments compose to create the intricate structure of modern cities, that cause new problems to the environment, not anticipated earlier, and only observed as they grow. There is a wide agreement that a single green roof has no positive impact on an urban environment. Though it is estimated that a major investment in large areas of vegetated roofs could make a substantial difference in solving the existing problems, eg. water management, heat island effect, urban biodiversity [9]. The private and public benefits would grow if the minimum area of the roofs was vegetated. What exactly is the required proportion is subject of research so far [16, p. 13]. As there are difficulties in estimating private financial benefits of installing a green roof [14, p. 7], and on the other hand it is proved that there are various public benefits, a major growth of green roof industry is strongly dependent on the support of state or local policies. Industrial premises because of their large size and infrastructures because of their public funding are often the first building types obliged to be vegetated [11]. Industrial architecture also often serves as a showcase and proof of the investor's commitment to green issues. Thus all types of vegetation can be found on the roofs of industrial and infrastructure buildings, though extensive sedum roofs strongly dominate.

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