Article

Modular Green Roofs for the Sustainability of the Built Environment: The Installation Process

Natalia Sergeevna Shushunova ^{1,*}, Elena Anatolyevna Korol ¹ and Nikolai Ivanovich Vatin ²

¹ Moscow State University of Civil Engineering, 129337 Moscow, Russia; professorkorol@mail.ru

² Institute of Civil Engineering, Peter the Great St. Petersburg Polytechnic University, 195251 St. Petersburg, Russia; vatin@mail.ru

* Correspondence: nshushun@gmail.com

Abstract: The research object is the installation process of modular green roofs with planters placed on the concrete roof's surface. These roofs effectively reduce rainfall disposal, prolong the lifespan of the roof coating, and enhance urban aesthetic and recreational spaces. Green roofs reduce houses' gas emissions and increase green spaces in densely built areas. The spatial–technological model was developed for the proposed modular green roof based on network planning, scheduling theory, and graph theory. The sequence and composition of technological processes and operations were established for the installation process. The functional model of installing a modular green roof has been developed. The model makes it possible to optimise the principles of saving labour contribution (working hours) and time.

Keywords: green roof; technological processes; modular green roof; multiphysics models; living environment; green building technologies; greenhouse gas emissions

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1. Introduction

Green roofs on buildings have multi-disciplinary benefits such as the improvement of rainfall disposal, the prolonged lifespan of the roof coating, the enhancement of urban aesthetic, and the creation of recreational spaces [1,2]. A quantitative analysis of 1623 English language sources indexed in Scopus from 1981 to 2020 shows that research on green roofs has steadily increased. Approximately 40.9% of the articles focus on regulating services in water, 30.0% on the thermal environment, and 3.5% on air quality [3]. Green roofs showed a surface temperature cooling effect [4,5]. The effects of urban heat islands [6] and global warming have led to an increased greening of cities as a tool for urban heat island mitigation in three main climate types: hot-humid, temperate, and dry [7–11]. Sustainability concerns have necessitated a shift towards sustainable urban water management systems, which could be analysed as multiphysics systems [12]. These systems include wet ponds, rain gardens, and green roofs [13]. Green roofs can contribute certain pollutants to rainfall disposal [14].

According to the 70th edition of Statistical Review of World Energy from British Petroleum in 2021 [15], the top five countries accounted for 59.4% of all CO₂ emissions. The largest emitter was China, as its share was 30.7%. The United States, with a share of 13.8%, was in second place; India, with a share of 7.1%, is in third place; Russia, with a share of 4.6%, is in fourth place; and Japan, with a share of 3.2%, is in fifth place. Therefore, it is necessary to establish full-fledged monitoring of this process on the planet.

The absorption of carbon dioxide could be achieved with an increase in green spaces in cities by creating green roofs and green walls on public buildings. Green roofs reduce houses' gas emissions and increase green spaces in densely built areas [16–21]. Another benefit of green roofs is that they offer new job opportunities; the larger the area, the more people are needed to design and maintain the roofing. Buildings with green roofs are

more attractive to tenants and buyers, which means they can be rented out and sold at a higher rate [22].

Green roofs can be integrated with photovoltaics, providing additional benefits compared to the conventional green roof. The various challenges hinder the large-scale implementation of photovoltaic–green roofs, including high initial costs, limited experimental data, and lack of awareness about the long-term benefits [23].

There are two possible green roof technological design types: stationary and modular.

On a stationary green roof, the primary layers are the waterproof and anti-root membranes; the protection, filter, and drainage layers; the substrate; and the vegetation. Commercial materials and products available in the market were provided, and innovative materials from recycled sources were analysed [24]. It is possible to use a three-layer concrete slab as a base coat for green roofs. The effectiveness of thermal insulation of a multi-layer, reinforced concrete slab using a layer of concrete with low thermal conductivity and properties of lightweight concrete under the conditions in tropical climates was studied in [25]. The thermal inertia of the extensive green roof in summer conditions was experimentally assessed [26–28].

There are no primary layers on the modular green roof in contrast to the stationary green roof. One of the modular green roof types was proposed by the authors E. Korol and N. Shushunova [29,30]. Planters with plants are placed on the concrete roof's surface [31,32]. Figure 1 shows the principal scheme of the modular green roof.

Figure 1. The principal scheme of the modular green roof proposed by the authors [31,32].

The main advantages of modular green roof systems over roll-out green roofs surround convenience and speed of the installation process. Green roof modules can be hand-balled into even the most awkward areas. They can be used to retrofit products for placing on existing conventional roofs [29]. Modular green roofs allow easy and quick replacement of plant pots during the entire life cycle of the roof.

However, no standard assessment methods exist to value green roofs, and balance between different services is lacking [3]. There is still a lack of comprehensive calculation of the economic merit of green roofs and walls, including their installation process, which has restricted the decision-making process [33]. Green roof implementation can be constrained by unsound economic assessment [34].

It follows from the above review that multiphysics processes have not been developed to optimise the technological processes of building green roofs. This study aims to create a spatial–technological model for the proposed modular green roof's installation, based on network planning, scheduling theory, and graph theory.

2. Materials and Methods

The research uses a formalised method for analysis of installing modular green roofs and defines the labour costs of technological processes and operations. The method is based on the principles of saving labour contribution (working hours) and time. Network planning, scheduling theory, and graph theory are used. The formal methods of expert assessment are also included [35].

3. Results and Discussion

The following mathematical model was built to calculate installation time and costs and to rationalise the installation organisation. The model of technological processes of the modular green roof installation consists of a spatial–technological model and a functional model (Figure 2).

Figure 2. The spatial–technological model and organisational and technological module (OTM).

The spatial–technological model consists of resource modules, front modules, and work modules. The resource module is the technological process’s minimum technical (labour) resource for performing a working operation (work module) with a volume equal

to its shift production. It occupies the necessary working space (front module) for this working operation. These elements make up the organisational and technological modules of individual technological processes of the modular green roof (Figure 2). Organisational modules and technological modules have different physical natures. The model describing all of them is multiphysical.

The installation process was divided into 24 sequential technological operations, listed in Table 1 in the technological sequence of expert assessment [35].

Table 1. The list of technological processes and operations of the organisational and technological module of the device of the modular green roof.

The Name of the Technological Process (Technological Operation)	Workers (Profession and Persons' Number)	Designation of the Process (Operation) in the Original List	Redesignation of the Process (Operation) in the Technological Sequence
Preparation of the base	Roofers of the 2nd category in the amount of two persons, roofer of the 3rd category in one person	x_1	y_6
Marking the covering for laying out the supports (levelling)	Roofers of the 2nd category in the amount of two persons, roofer of the 3rd category in one person	x_2	y_7
Layout and gluing of supports	Roofers of the 2nd category in two persons, roofer of the 3rd category in one person	x_3	y_8
Support tilt angle adjustment	Roofers of the 2nd category in two persons, roofer of the 3rd category in one person	x_4	y_9
Fastening the clips	Roofers of the 2nd category in two persons, roofer of the 3rd category in one person	x_5	y_{10}
Laying and fixing the grating on the supports	Roofers of the 2nd category in two persons, roofer of the 3rd category in one person	x_6	y_{12}
Installation and connection of a group of modules in the amount of 4 pcs. fixed to the gratings	Roofers of the 2nd category in two persons, roofer of the 3rd category in one person	x_7	y_{14}
Preparation and transportation of the materials	Riggers of the 2nd category in two persons, driver of the 4th category in one person, driver of the 6th category in one person, ancillary worker of the 2nd category in one person	x_8	y_4
Supply of concrete mix solution in boxes by truck crane	Riggers of the 2nd category in two persons, driver of the 4th category in one person	x_9	y_{13}
Transportation of materials (goods) by hand carts	Ancillary worker of the 2nd category in one person	x_{10}	y_{14}
Feeding materials to the roof by crane	Riggers of the 2nd category in two persons, driver of the 6th category in one person	x_{11}	y_5
Installation of planters	Roofers of the 2nd category in two persons, ancillary worker of the 1st category in one person	x_{12}	y_{17}
Filling a group of modules with soil and planting material	Roofers of the 2nd category in two persons, ancillary worker of the 1st category in one person	x_{13}	y_{19}

Table 1. Cont.

The Name of the Technological Process (Technological Operation)	Workers (Profession and Persons' Number)	Designation of the Process (Operation) in the Original List	Redesignation of the Process (Operation) in the Technological Sequence
Operational control of the technological process	Master	x_{14}	y_{18}
Incoming inspection of materials	Master	x_{15}	y_1
Verification of compliance with the project arrangement of roof elements	Master	x_{16}	y_2
Checking the conformity of the project of the incoming materials	Master	x_{17}	y_3
Quality of preparation of the coating base	Master	x_{18}	y_{15}
Control of the technical condition of technological equipment	Master	x_{19}	y_{16}
Quality control of finished joints of structural elements	Laboratory assistant, roofer of the 3rd category, master	x_{20}	y_{20}
Visual control	Roofer of the 3rd category	x_{21}	y_{21}
Control of geometric parameters of roof elements	Master	x_{22}	y_{22}
Non-destructive testing methods	Laboratory assistant	x_{23}	y_{23}
Testing of roof structures and materials	Laboratory assistant	x_{24}	y_{24}

The algorithm for constructing a spatial and technological structural model was divided into the following stages:

1. Construction of a matrix of technological links of organisational and technological module processes based on the results of an expert assessment of the succession–precedence of technological processes (operations) in paired comparisons.
2. Creation of a graph of the technological sequence based on the matrix data (excluding compound operations).
3. Fragmentation of the graph into specific layers (finding and filtering out paths resulting from the transitivity property).
4. Creation of the final graph of the spatial and technological structure of the organisational and technological module.

First, the technological ordering of the processes and construction of a matrix of technological links of organisational and technological module processes was carried out based on an expert assessment of the succession–precedence of technological processes (operations) in paired comparisons. It is required to find a sequence Y_i that is a permutation of the sequence X_i such that the fact that $Y_i \ll Y_j$ implies that $i < j$. The “ $\ll$ ” sign was introduced to denote the order in the technological sequence of processes, namely when the sequence X_i precedes the sequence X_j .

The conventions for the matrix X_{ij} elements were introduced to do this ordering. The conventions are as follows:

- (1) $X_{ij} = 1$ if $X_i \ll X_j$
- (2) $X_{ij} = 0$ if $X_j \ll X_i$
- (3) $X_{ij} = n/a$ if condition 1 and condition 2 are not met.

- (4) $X_{ij} = c$ if one of the elements is an integral part of the other.
- (5) $X_{ij} = "?"$ if the relationship between a simple and a composite technological operation cannot be determined.

Figure 3 represents the resulting matrix X in the form of a technological sequence. The matrix is divided into layers so that all the elements of this layer do not have predecessor works in this, and previous layers and the elements of the first layer do not have predecessor works. The elements of the last one do not have successor works.

	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	X15	X16	X17	X18	X19	X20	X21	X22	X23	X24
X1	0	c	c	c	c	c	c	n/a	n/a	n/a	n/a	1	1	n/a	0	?	0	1	1	1	1	1	1	1
X2	c	0	n/a	n/a	n/a	1	1	n/a	n/a	n/a	n/a	1	1	n/a	0	0	0	1	n/a	1	1	1	1	1
X3	c	n/a	0	n/a	n/a	1	1	n/a	n/a	n/a	n/a	1	1	n/a	0	n/a	0	1	1	1	1	1	1	1
X4	c	n/a	n/a	0	n/a	1	1	n/a	n/a	n/a	n/a	1	1	n/a	0	0	n/a	1	n/a	1	1	1	1	1
X5	c	n/a	n/a	n/a	0	1	1	n/a	n/a	n/a	n/a	1	1	n/a	0	0	n/a	1	1	1	1	1	1	1
X6	c	0	0	0	0	0	1	n/a	n/a	n/a	n/a	1	1	n/a	0	n/a	n/a	1	1	1	1	1	1	1
X7	c	0	0	0	0	0	0	0	0	0	0	1	1	n/a	0	0	0	n/a	n/a	1	1	1	1	1
X8	c	n/a	n/a	n/a	n/a	n/a	1	0	c	c	c	1	1	n/a	n/a	n/a	n/a	n/a	1	1	1	1	1	1
X9	n/a	n/a	n/a	n/a	n/a	n/a	1	c	0	0	0	1	1	1	c	n/a	0	n/a	1	1	1	1	1	1
X10	n/a	n/a	n/a	n/a	n/a	n/a	1	c	1	0	0	1	1	n/a	n/a	n/a	0	n/a	1	1	1	1	1	1
X11	n/a	n/a	n/a	n/a	n/a	n/a	1	c	1	1	0	1	1	n/a	n/a	n/a	n/a	n/a	1	1	1	1	1	1
X12	0	0	0	0	0	0	0	0	0	0	0	0	c	n/a	0	0	0	0	0	1	1	1	1	1
X13	0	0	0	0	0	0	0	0	0	0	0	0	c	0	n/a	0	0	0	0	0	1	1	1	1
X14	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0	n/a	n/a	n/a	n/a	0	0	0	0	0	0	1	1	1	1	1
X15	1	1	1	1	1	1	1	n/a	c	n/a	n/a	1	1	1	0	c	c	1	n/a	1	1	1	1	1
X16	?	1	n/a	1	1	n/a	1	n/a	n/a	n/a	n/a	1	1	1	c	0	n/a	n/a	n/a	1	1	1	1	1
X17	1	1	1	n/a	n/a	n/a	1	n/a	1	1	n/a	1	1	1	c	n/a	0	n/a	1	1	1	1	1	1
X18	0	0	0	0	0	0	n/a	n/a	n/a	n/a	n/a	1	1	1	0	n/a	n/a	0	n/a	1	1	1	1	1
X19	0	n/a	0	n/a	0	0	n/a	0	0	0	0	1	1	1	n/a	n/a	0	n/a	0	1	1	1	1	1
X20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	n/a	n/a	n/a	n/a
X21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	n/a	0	n/a	n/a	n/a
X22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	n/a	n/a	0	n/a	n/a
X23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	n/a	n/a	n/a	0	n/a
X24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	n/a	n/a	n/a	n/a	0

Figure 3. The matrix of technological links of individual technological processes (operations) of the device of the modular green roof.

The following algorithm was introduced for this division:

- All the rows of the matrix that satisfy the condition: $i \neq j$, $X_{ij} \neq 0$ are found.
- The elements $X_{ij} \neq 0$ are replaced in the first layer of the row in which they are found.
- Elements X_{ij} belonging to the next layer are found. It is necessary to find such rows X_i that $i \neq j$, $X_{ij} = 0$ implies that the row X_i is contained in the set of layers from the first layer to the layer under consideration.

This algorithm for fragmentation of the graph into layers is finished when all rows X_i that do not contain ones are found.

Figure 4 shows the results as a graph of the technological structure of the organisational and technological module with fragmentation into layers so that the processes (operations) are technologically independent. Hence, the processes (operations) can be performed in parallel.

Figure 4. The graph of the technological structure of the organisational and technological module (OTM) of the technological process of the device of the modular green roof.

The constructed graph indicates technological operations in the form of elements X_{ij} of the matrix. The arrows show the technological connections between operations. Based on the constructed graph, the following can be established:

- (1) Technological operation X_{15} is composite.
- (2) It includes operations X_9 , X_{16} , X_{17} , which may be present in any of 1–3 layers.
- (3) Technological operation X_{14} is not composite. It may be executed in parallel with operation X_{12} .
- (4) Based on the results of constructing the graph, the cycles are eliminated.

After constructing the graph, a new list of technological processes and operations of organisational and technological modules for the green roof was compiled, indicating the workplaces of the work. The technological operations are numbered in this list based on their technological sequence. In the graph, simple technological operations that are not a part of others begin with the capital letter “Y” and compound operations with the lowercase “y”. As a result of these operations’ spatial and technological ordering based on network planning methods, a model (graph) of the “top-work” type was formed (Figure 5).

The “=” sign was introduced to denote the relationship of spatial equivalence. The rule of the denotation is as follows: if $Y_i, Y_j \in Y_i \& k_i = k_j$, then $Y_i = Y_j$. This relation is reflected in the graph of the spatial structure of the technological process. Connections of spatial equivalence were established in the places where it is possible to perform them in a specific subspace. There,

k_1 is the main subspace, i.e., the class of spatial equivalence of the working area of the roofing device (connections between operations performed in the working area);

k_2 is the class of spatial equivalence: site of acceptance and preparation of materials (serving subspace); and

k_3 is the spatial equivalence class of the testing laboratory (serving subspace).

Then, a graph of resource equivalence of a roofing device with modular landscaping is built (Figure 6), and the performers of technological processes and operations are assigned the corresponding numbers—resource equivalence classes (I):

l_1 is the labour resource equivalence of the class: master in the amount of one person;

l_2 is the labour resource equivalence of the class: rigger of the second category in the amount of two persons, driver of the sixth category in the amount of one person;

l_3 is the resource equivalence class: ancillary worker of the second category in the amount of one person;

l_4 is the resource equivalence class: roofer of the second category in the amount of two persons, roofer of the third category in the amount of one person; and

l_5 is the resource equivalence class: laboratory assistant in the amount of one person.

Figure 5. The graph of the spatial structure of the organisational and technological modules. Wa—working area; Lab—testing laboratory.

Figure 6. The graph of the distribution of labour resources of the organisational and technological module of the technological process of the device of a modular roof.

Classes of spatial equivalence k and classes of resource equivalence l are introduced to assess technological operations that can be performed in parallel (up to the front module).

The organisational and technological module was developed after the spatial and technological structure were constructed and the technological and spatial ordering of technological processes were formed.

In the functional model, for each technological process (technological operation), the value of its execution time t_{ijkl} is introduced, where:

i is the index of the sequence element (operation number), $i = 1, 2, \dots, 24$;

j is the number of the layer in which the operation is located, $j = 1, 2, \dots, 6$;

k is the number of the main or serving subspace, $k = 1, 2, 3$; and

l is the number (class) of the labour resource, $l = 1, 2, \dots, 5$.

In this case, the value t_{ijkl} can be unambiguously replaced by the value t_1 as $t_{ijkl} = t_1$ (Figure 7).

Figure 7. The graph of the functional model of the organisational and technological module.

With the formed structural and functional model, the total duration of the operations of the main subspace of the organisational and technological module is found according to the formula:

$$T_{OTM} = \sum_{j=1}^7 f(t_{i_n,j,k,l_n}, f(t_{i_{n-1},j,k,l_{n-1}}, f(t_{i_2,j,k,l_2})) \dots) \quad (1)$$

where n for each j is the number of elements in the layer,

$$(t_{i_n,j,k,l_n}, t_{i_{n-1},j,k,l_{n-1}}) = \begin{cases} t_{i_n,j,k,l_n} + t_{i_{n-1},j,k,l_{n-1}}, & \text{if } l_1 = l_2 \text{ (sequential work of one resource)} \\ \max(t_{i_n,j,k,l_n}, t_{i_{n-1},j,k,l_{n-1}}), & \text{if } l_1 \neq l_2 \text{ (parallel work on two resources)} \end{cases} \quad (2)$$

The duration of work in the main subspace is decisive for the remaining subspaces and adjacent processes. Therefore, work operations in the serving subspaces can begin at earlier times than in the main subspace.

Thus, creating the structural–functional model makes it possible to determine the main indicators of the organisational efficiency of installing the modular green roof.

4. Conclusions

The research object is the installation process of modular green roofs with planters placed on the concrete roof's surface. These roofs effectively reduce rainfall disposal, increase the prolonged lifespan of the roof coating, and enhance urban aesthetic and recreational spaces. Green roofs reduce houses' gas emissions and increase green spaces in densely built areas.

One of the modular green roof types was proposed by the authors E. Korol and N. Shushunova [29,30]. However, no standard assessment methods exist to value green roofs, and balance between different services is lacking [3]. There is still a lack of comprehensive calculation of the economic merit of green roofs and walls, including their installation process, which has restricted the decision-making process [33]. Green roof implementation can be constrained by unsound economic assessment [34].

The spatial–technological model was developed for the proposed modular green roof based on network planning, scheduling theory, and graph theory. Analysing the model led to the following conclusions:

- (1) The sequence and composition of technological processes and operations was established for installing the modular green roof.
- (2) The spatial and technological structure model has been built as a result of the formation of technological and spatial ordering of technological processes.
- (3) The functional model of installing a modular green roof has been developed. The model makes it possible to optimise on the principles of saving labour contribution (working hours) and time.

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