

Article

A Dynamic Model for Effective and Optimal Planning of Formwork in Construction Projects

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Abstract: The cost of producing one cubic meter of concrete structure, depending on the structure's shape, type, and complexity, can be variously high. The cost of concrete, reinforcement, formwork, and labor ratio varies. But unlike the cost of concrete and reinforcement, which tend to be similar in the terms of the conditions of a particular construction project, the cost of formwork and work with it are different for different contractors. It often depends on the appropriateness of the formwork system used, the optimal placement of the formwork sets, the minimization of downtime, and the efficiency of the carpenters' work. Formwork modeling in the construction preparation phase intervenes in this planning area, where construction sources are defined and quantified, and the time course of their deployment is determined. The current paper deals with optimizing formwork selection and deployment in concrete structure execution. Even if several requirements must be considered when selecting and modeling the formwork (e.g., construction time, quality of concrete structure, etc.), an effort to minimize the cost of formwork, and thus construction cost, plays the most significant role. A dynamic model for effective and optimal planning of formwork in construction projects, including formwork cost analysis, is presented in the paper. The included case study demonstrated the planning of the formwork through a software application developed based on the computational algorithm of the dynamic model presented. A case study is presented in the article as a research method. An office building with five above-ground floors and one underground floor was chosen for the case study. To solve the case study, the formwork for horizontal structures (i.e., beams and slabs) is considered. The goal of the case study is to identify research questions and apply time and cost optimization to a selected specific building.

Keywords: formwork; concrete structure; modeling; cost of formwork; construction time



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1. Introduction

Currently, much attention is being paid to the efficient planning of construction projects. Effective construction planning focuses on reducing costs, protecting the environment, and ensuring sustainability. Considerations for choosing an appropriate formwork system for monolithic concrete structures include construction geometry, labor productivity, safety, costs, time, and the visual appeal of the concrete structures' surfaces [1]. The role of formwork is to make a structure of the desired shape from concrete after its hardening. The formwork defines the desired shape and size of concrete structures and determines their location in the building. The most common feature of this temporary load-bearing structure is that it can be removed after concrete hardening or, if necessary, left in place as lost formwork. If the formwork components are intended for multiple uses, they can be moved to the next zone of the building or to another construction site [2,3]. The formwork cost is a significant part of the total budgeted cost of the entire concrete structure. Previous research studies have shown that the cost of formwork represents an average of 25% of the cost of the entire concrete structure [4–6]. It is possible to reduce the cost through the adoption of

modern methods of construction [7]. The construction cost, construction time, and quality of a construction project are all impacted by the formwork choice [8,9]. In their research studies, Dongmin Lee et al. [10] and Usmanov et al. [11] proposed the optimization of the production of formwork of irregular shapes. Such an approach represents an improvement in the efficiency of work in formwork production. Lee et al. stated in their study that the formwork cost was reduced by 14.1% due to the application of the Harmony Search Algorithm (HSA) [10]. The need for the proper design of the formwork was addressed in the research of Guo et al. [12], who dealt with the design of formwork for the construction of concrete shells. Some other authors have also dealt with the proper design of formwork [13]. Reducing the cost of formwork can be achieved by making maximum use of material and time and making the design, assembly, and disassembly more efficient [14,15]. Other authors have proposed a method to automate the data from the formwork displayed in 2D CAD into the 3D BIM model of the building [16]. They developed the formwork automation design software tool based on the conversion of randomly arranged vertices among the BIM data of the target structures to a specific form based on certain rules, followed by the setting of specific rules for the face. The availability of a 3D BIM model of complex structures allows the formwork manufacturer to quickly incorporate shared changes from the concrete structure designer [17]. Some researchers have tried integrating elements of robotics into the production of concrete structures by using formwork [18,19]. In contrast, other authors have adopted 3D-printing technology to produce permanent formwork [20]. Three-dimensional printing can also be used to make concrete structures without formwork; for example, researchers Hoffmann et al. presented a study dealing with concrete piles' production by adopting 3D printing in this way [21]. The effectiveness of the formwork use can be measured by virtual cost, i.e., when the formwork is placed on the construction site without the need for it to be incorporated into the structure [22]. For example, a study from Malaysia confirmed that traditional formwork reduced the cost of some concrete structures compared to the use of system formwork [23]. At the same time, formwork material and wages are among the highest costs in building reinforced concrete structures [21,24]. In the case of large-scale projects, within the implementation phase of the building's life cycle, the cost of formwork represents a significant part of the production budget of the reinforced concrete skeleton [25]. Similar to our study, Baraneetharan E. stated that formwork is a temporary structure providing support, shape, and strength to the fresh concrete until it reaches its required strength. This study identified the different types of formwork used in construction and analyzed the factors influencing the choice of formwork [26–28]. There is also a study that estimated the required hours of work on the formwork of reinforced concrete-frame buildings using artificial neural networks [29]. The modeling of the formwork in the building-technological preparation of construction intervenes in this area of planning where construction sources are defined and quantified, and the time course of their deployment and drawing is determined. Information on the formwork of concrete structures is mostly processed as a formwork plan. The contractor draws up the formwork plan or arranges for it to be developed by a specialized institution as part of the production preparation of construction.

Usually, formwork modeling aims to select the optimal material and type of formwork and suggest an optimal schedule for the formwork used from a construction cost or construction time point of view. Similar to our paper, the study of Mansuri, D. et al. [15] incorporated the presentation of a case study where the developed tool was applied to a construction project in Cincinnati, Ohio, and a 13% saving in formwork material costs was recorded.

The transport processes as transport of the primary material (formwork, reinforcement, ready-mix concrete) and measurement and check processes are also parts of the production process. The natural physicochemical process of concrete hardening is carried out together with the production process. Its course influences the duration of necessary technological breaks after placing and compacting concrete. The duration of technological breaks is important not only in terms of a partial or total formwork removal point of view, but also

in terms of immediately following processes running in the space defined by executing the concrete structure. The duration of a technological break is defined in a schedule as the time gap between immediately following processes. Determining the size and direction of the working queue development for different processes (technological stages) presents one of the key moments in designing an optimal construction schedule. The level of detail in a construction schedule of concrete structure execution and the related time–spatial program of the formwork used depends on the building requirements. When requesting the lower level of details in scheduling, the partial construction processes are aggregated into one working zone, one floor, a whole building, etc.

The presented study points to the need for optimal formwork selection and planning in the construction of monolithic concrete structures. For selection and planning to be optimal, it is necessary to know in detail all the modeling inputs, such as the material, financial, and time parameters of construction. This can minimize the construction cost and construction time and avoid unnecessary waste.

The significance of research on the modeling of formwork use in construction consists of pointing out the necessity of optimizing the total costs of the constructed reinforced concrete structures or the construction time needed to build the structures. Such optimization of costs and time is required due to compliance with the principles of sustainability in the construction process. Reducing the costs of reinforced concrete construction is an economic pillar of sustainability. The environmental pillar of sustainability is ensured by less consumption of formwork material, i.e., greater turnover of formwork. The goal is to limit the one-time use of formwork or a small number of repetitions of its use and to use formwork as repeatably as possible up to the limit of its economic life. The social pillar of sustainability can be reflected in a shorter time of the construction's impact on the surrounding environment due to the optimized construction time of the reinforced concrete structure.

The innovation of the current study is that it is possible to prove that without dealing with optimization in the selection and deployment of formwork in construction, it is not possible to fully ensure the sustainability of the construction of reinforced concrete structures. An innovative approach is considered to be an approach that emphasizes the more time-consuming development of an optimized formwork project, which will ultimately ensure a reduction in costs and time, which the study has confirmed. Meanwhile, only the auxiliary structure of the construction, which is not permanently incorporated into the building, is optimized.

2. Materials and Methods

Formwork is utilized in the construction of monolithic concrete structures. Execution of monolithic concrete structures within the framework of a building is a space-making process. The schedule of formwork use is developed separately for vertical and horizontal structures. In the case of multi-story buildings, the conditionality of vertical and horizontal structures must be considered when scheduling.

The construction process of a monolithic concrete structure execution involves the following processes: (i) formwork mounting: installation of the formwork for a concrete structure; (ii) reinforcing: preparation of necessary reinforcement and placing it onto the formwork; (iii) concreting: production, transport, and casting of concrete; (iv) concrete curing; and (v) formwork dismantling: removal of formwork components, either partial or full.

The study presented includes the steps to develop a dynamic model for effective and optimal planning of formwork in construction projects:

- i. determination of the topic, choice, and definition of the optimization problem;
- ii. literature study and overview of research on issues, such as modeling the deployment of formwork in construction and modeling the formwork cost in construction;
- iii. study on analytical and numerical methods to optimize the formwork costs and choice of the right study method;

- iv. specification of inputs to dynamic modeling of formwork deployment;
- v. proposal of a mathematical method to summarize formwork elements;
- vi. design of a model to summarize formwork costs and formwork cost analysis;
- vii. case study to illustrate the comparison of several variants from the formwork cost point of view.

2.1. The Time Analysis of Formwork Components Used in Building Zones

The activities going on successively that are related to the delivery and use of formwork components are the basis for the time analysis of formwork used in a building. The progress phases of formwork used in a building include the following in particular: (i) delivery and preparation of formwork components; (ii) installation and use of formwork in the building zones; and (iii) removal of formwork from the building. The delivery and preparation of formwork components incorporates the following: (i) transport into a building site; (ii) handling/storage of formwork components in a common storing place or directly in the building zone; and (iii) mounting of formwork components onto larger planar and triaxial units/assemblies before their first installation in the building zones. The process of installation and use of formwork in the building zones includes (i) treatment and transport of formwork into the place of its use; (ii) mounting of components or installation of formwork assemblies; (iii) use of formwork in the zone when formwork is bearing the full or partial load of construction; (iv) removal and partial or complete release of the formwork from the building zone; (v) and treatment and transport of formwork to a place of its subsequent use in the building or to a storing place (when using the formwork successively in various building zones, the activities of this phase are repeated). The last process, removal of the formwork from the building, covers (i) dismantling of the formwork and deposition of components into figures or palettes and (ii) removal of the formwork from the construction site.

The construction schedule of the building framework is presented in Figure 1. Five floors represent the five building zones, i.e., “1. Floor, 2. Floor, 3. Floor, 4. Floor and 5. Floor”, of the building. The building framework consists of a brick exterior (450 mm thick), inner walls (300 mm thick), and reinforced concrete monolithic slabs (200 mm thick). Moreover, there is a monolithic concrete staircase on each floor. The following terms imported from the formwork of concrete slabs’ point of view are defined graphically: the term of the beginning of formwork mounting in the building zones and the term of concreting finish; the term of partial removal of the formwork and parts of the supporting structures after the technological break when the concrete has reached the required strength; and the term of the full removal of the formwork, i.e., removal of additional supporting components of the slab formwork.

In this example, the components of the formwork cannot be immediately used in the second zone after removal from the first zone since the mounting of the formwork for the second zone is planned in the time before formwork removal from the first zone. During the execution of concrete slab structures, the formwork components for two zones (floors) and a set of supporting pillars for partial slab support are available at the site. A time interval may arise between the earliest possible term of formwork removal in the previous zone and its mounting (installation) in the following zone. The formwork components are available for longer than necessary from their use point of view. The following possibilities may occur during the interval: (i) the formwork components remain installed for longer in the previous zone or (ii) the formwork components are removed and are waiting for use in a temporary storage place.

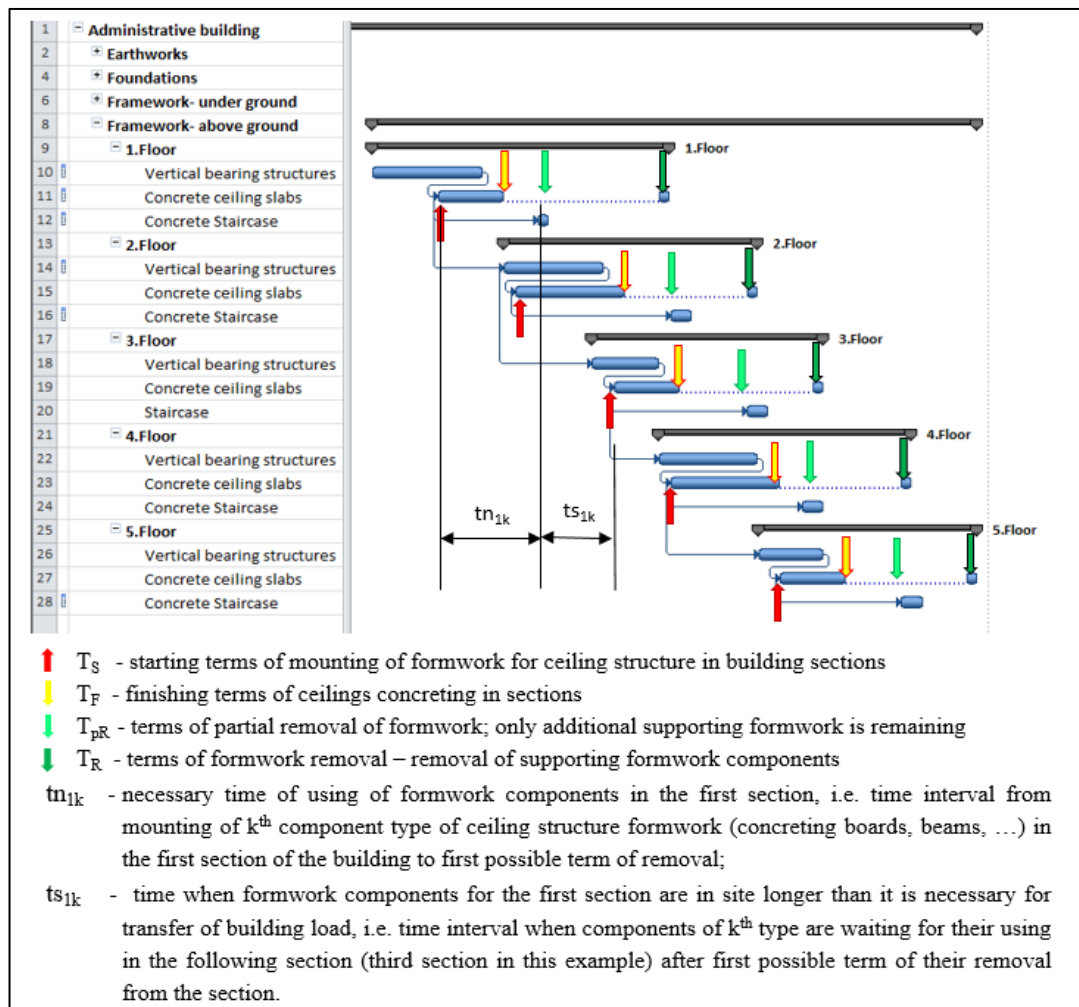


Figure 1. The terms important from formwork use point of view.

The total use time t_{ik} of the k^{th} formwork component in the i^{th} construction zone is determined by the following formula:

$$t_{ik} = tn_{ik} + ts_{ik} \quad (1)$$

while

$$tn_{ik} = \sum_{j=1}^m t_{ji} + tb_k \quad (2)$$

where

i : indication/number of the zone;

k : type of formwork components, for example, concreting boards, beams, supporting components or systems, column formwork, working platforms, etc.;

t_{ik} : total time of use of k^{th} type formwork components in the i^{th} construction zone [day];

tn_{ik} : necessary time of use of k^{th} type formwork components in the i^{th} construction zone [day];

ts_{ik} : time when k^{th} type components from the i^{th} construction zone is in the building longer than it is required to transfer the construction load (components remain in a construction zone or they are placed in temporary storage after removal from the i^{th} zone), i.e., the time interval when k^{th} type components are waiting for use in the following zone after removal from the previous zone [day];

m : number of partial processes (transport of the formwork into the zone, i.e., removal and transport of the formwork from the previous zone or transport of the formwork from the storage place, mounting of the formwork, reinforcing, and concreting);
 t_{ji} : duration of the j^{th} partial process in the i^{th} construction zone, where the duration of partial processes (formwork mounting, reinforcing, and concreting) depends on the amount of the work in the zone and on the intensity of construction resources [day];
 t_{bk} : technological break after concreting; after the break, it is possible to remove the k^{th} type components from the zone (it may be different in diverse types of formwork components) [day].

In the case of a parallel course of partial processes in a construction zone, i.e., some partial processes (formwork mounting and installation, reinforcing and concreting) run at the same time in the zone but are displaced, the necessary use time tn_{ik} of k^{th} type formwork components in the i^{th} construction zone is determined by the following formula:

$$tn_{ik} = (T_{Fi} - T_{Si}) + tb_k \quad (3)$$

where

tn_{ik} : necessary (minimum needed) time of the k^{th} type components used in the i^{th} construction zone,

T_{Fi} : term of concreting finish in the i^{th} construction zone [date];

T_{Si} : term of the start of formwork mounting in the i^{th} construction zone; mounting works usually begin with the transport of components from the storage place, followed by formwork removal and transport of components from the previous zone [date];

t_{bk} : technological break after concreting, after which it is possible to remove the k^{th} type components from the zone [day].

The duration of the period from concrete placing into the formwork until the planned beginning of formwork removal is crucial for the start of formwork removal. The technological break is essential for the natural process of concrete hardening, after which the concrete structure acquires the features necessary for the beginning of the follow-up process. When scheduling the construction, it is essential to consider the technological breaks that are inevitable in concrete hardening. In order to avoid mistakes in scheduling, it is necessary to be aware of construction works' continuity.

In the case of vertical structures (walls, columns), formwork removal is the downstream process that occurs after concrete placing and compacting. In this case, the formwork is removed after 24 h, followed by 48 h of concrete hardening. Form removal depends on concrete features and climatic conditions.

Unlike vertical concrete structures, the removal of ceilings' formwork starts when some construction works in the following floor have begun or been finished. In the case of ceiling slabs, the downstream process after placing and compacting the concrete is represented by the execution of vertical-bearing structures on the following floor of the building. The technological break is essential to make the concrete of the ceiling structure so hard that it is not damaged by the movement of the formworking team, the transport of material, or the work of masons if the vertical-bearing structures are not concrete. The break is short, usually 24 h for slabs with concrete flooring layers of floors. The loading of the freshly concreted board by material and by the execution of vertical structures is transferred to supporting components of the formwork.

Some contractors comply with the German standard DIN 1045 Beton und Stahlbetonbau, paragraph 12.3.1. when considering the time limits of formwork removal. This standard established the conditions and time of formwork removal, as well as the time and conditions of the removal of supporting structures dependent on the class of cement used. It is impossible to use the mathematical formula given for one construction zone when determining and planning the time of formwork used in a structure composed of a few construction zones. The total time of different components used is limited by the term of delivery of the formwork components into the site and by the term of their transport

away from the site. The period of the k^{th} type component used on site depends on the composition of formwork components in different zones and on the work schedule in the zones, including necessary technological breaks. When scheduling construction, a sequential, parallel, and current method of construction work flow may be applied. The formwork components may be used once or repeatedly in multiple zones during their availability at the site.

2.2. The Cost of Formwork

The cost of formwork creates about 25% of the concrete construction total price. The cost of formwork includes the cost of formwork elements (purchase, depreciation, rental, etc.) and the costs created in the forming process. The formwork erection in an RC (reinforced construction) building project takes up to 15% of the total construction cost or 1/3 of the total concrete cost [30]. Using a traditional concrete formwork system may be considered a labor-intensive and time-consuming operation. According to various surveys, the proportion of labor for mounting and dismounting the construction formwork of reinforced concrete structures for aggregate processes for road construction is, on average, about 30%. Even studies abroad show comparable results in the tracking of costs for formwork. For example, the installation of formwork for reinforced concrete structures is about 15% to 20% of the total cost of raw building or 30% to 35% of the cost of constructing reinforced concrete structures. Differences in mean costs are due to territorial differences in the price of labor and materials.

The share of the cost of auxiliary structures is high, so interest in their reduction is justified. In this respect, this group of auxiliary structures stands out mainly in terms of construction formwork. The cost of formwork formed in Slovakia and the Czech Republic, according to Ladra, currently averages around 25% of the total price of the concrete structure, which is proportional to the labor-intensive process of shuttering [31].

Analysis of the cost needed for the formwork of reinforced concrete structure in one working zone of an object/building is a basis for analyzing the total cost of formwork of an object/building. The formula for calculating the cost for formwork in the i^{th} working zone is as follows:

$$C_i = Cm_i + Cfc_i + Cr_i + Cmc_i \quad (4)$$

Costs for formwork for more working zones are calculated according to the formula:

$$f = \sum_{i=1}^z Cm_i + Cfc_t + \sum_{i=1}^z Cr_i + \sum_{i=1}^z Cmc_i \quad (5)$$

where

C_i : cost of formwork in the i^{th} working zone [EUR];

Cm_i : cost of mounting of formwork in the i^{th} working zone [EUR];

Cr_i : cost of removal of formwork in the i^{th} working zone [EUR];

Cfc_i : cost of formwork components of the i^{th} working zone (purchase, depreciation, rent, etc.), i.e., price of formwork elements for one-time use; if formwork elements are intended for multiple uses, it is the amount of depreciation (if the implementation company has purchased its own formwork) or lease (rental fees for formwork), calculated for the period deployment/use of formwork elements in the i^{th} working zone [EUR];

Cmc_i : cost of maintenance and cleaning formwork elements at the time of deployment in the i^{th} working zone [EUR];

Cf : total cost of formwork (all working zones) [EUR];

z : number of working zones;

Cfc_t : total cost of formwork components of all working zones [EUR].

Effective costs, performance, and safety can also be achieved with the right material solution of the formwork. In certain construction projects, using traditional timber formwork is considered to be an effective formwork solution [32]. However, it is also

necessary to consider the shape errors of the formwork. Some research studies suggested the production of precise building formwork using laser cutting equipment [33]. There are also concrete structures, in the construction of which special formwork materials are used. In their research study, Li W. et al. examined special sand forms [34]. Other authors applied formwork from a flexible cable-net and knitted fabric formwork system [35]. The lightweight formwork was easy to transport, reducing the need for additional scaffolding and simplifying site logistics. In the case of complicated formwork, its digital manufacturing appears to be uneconomical and labor-intensive, whereas digital processes should be sustainable and competitive [36–39].

Modern formwork systems in combination with traditional systems offer practical, easy-to-implement solutions for a more sustainable way of construction. For large construction projects with more iterations and modular construction, modern formwork systems always have more advantages than disadvantages [40]. There are formwork planning software tools on the market, but they do not always ensure optimal solutions that minimize formwork costs [41,42]. Considering the high proportion of formwork costs, it is often necessary to optimize the formwork proposals obtained through these tools. The current study offers possible optimization of the formwork proposal.

3. Results

3.1. The Design of the Model for Summarization of the Formwork Components and Cost Analysis

The basic mathematical algorithm of the dynamic model for summarization of the formwork components considers the inputs from the construction schedule and the plan of the formwork, as well as the technological properties of concrete in real construction conditions. The summarizing results are then reflected in the calculation of the cost of the formwork components or the calculation of the overall cost of the formwork, depending on the time of execution of the concrete structures of the building. The calculation of the cost of formwork components is based on the following assumptions (Figure 2):

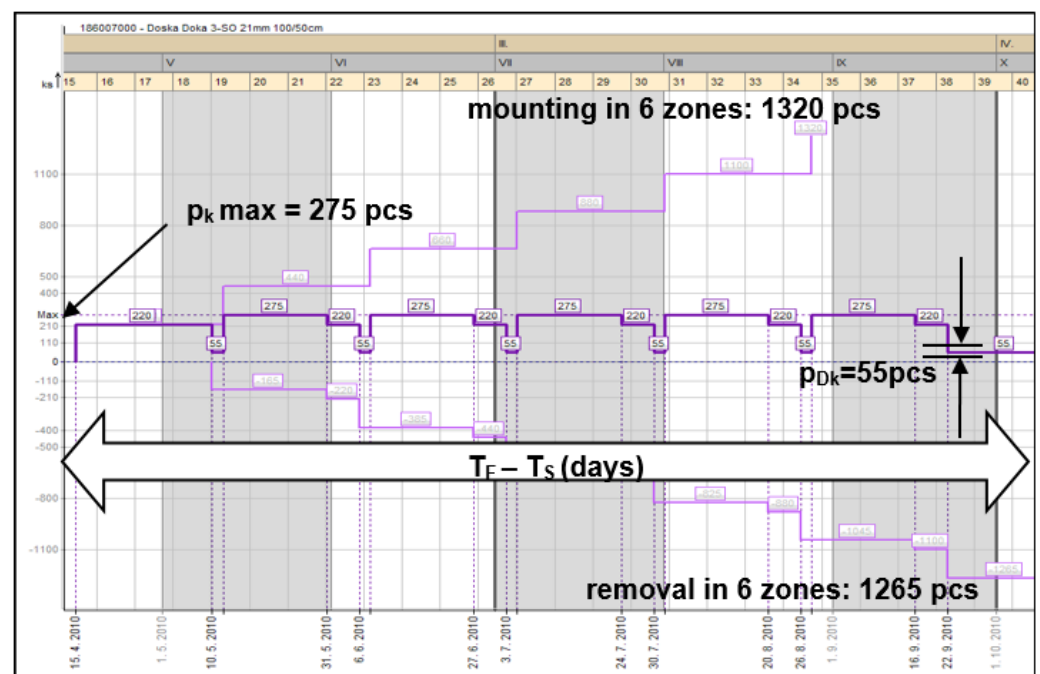


Figure 2. Histogram and cumulative charts of mounting and removal of the formwork boards.

Components/sets of the k th type of the formwork are in the site available in the interval from T_S to T_F in the total amount p_{kmax} , where T_S is the term of components' delivery into the site, i.e., the planned term of the start of formwork mounting in the first zone of the construction, and T_F is the term of formwork removal in the last zone of

the construction. Components of the k th type of the formwork in the number p_{Dk} are delivered to the site in the term T_S , and they remain in the building as a lost formwork or are “consumed/degraded” during construction.

The crucial input information for the dynamic modeling of the formwork deployment incorporates the following: construction schedule; technological parameters of concrete in the particular construction conditions; and the design documentation of the formwork project. The ultimate information on the time parameters, such as the number of working zones in construction, start date of formwork montage in the individual zones of construction, and dates of concreting finish or implementation process duration of concrete construction in particular zones, is involved in the construction schedule. The technological parameters of concrete in particular construction conditions consider a technological break after concreting for the gain of concrete strength needed for partial formwork removal of construction, as well as a technological break after concreting for the gain of concrete strength needed for total formwork removal of construction. The design documentation of the formwork project serves to consider the data as follows: (i) bill and price of elements/completes of a particular formwork system for individual zones of construction; (ii) quantity of elements/completes for individual zones at total exploitation of formwork; (iii) quantity of elements/completes for individual zones at partial exploitation of formwork; (iv) quantity of elements/completes for individual zones at one-shot exploitation of formwork; and (v) conversion index of costs for rental or depreciation of system formwork elements/competes on the basis of price and formwork duration of its exploitation in construction.

The formula for calculation of the formwork components' cost presents a purposeful function in the formwork use optimization task. The task minimizes the function as follows:

$$Cfc_t = C_F + \sum_{k=1}^S ((p_{kmax} - p_{Dk}) \times (T_F - T_S) \times c_k \times f_k) \quad (6)$$

where

Cfc_t : total cost of formwork components of all working zones [EUR];

C_F : fixed cost of the formwork components in a zone/construction, i.e., the price p_{Dk} of lost formwork elements and price of consumables, elements, and preparations included in the formwork [EUR];

S : number of types of formwork components, for example, concreting boards, beams, bearing and supporting elements or systems, sets of columns formwork, working platforms, etc.;

p_{kmax} : number of k^{th} type formwork components available at the site [pc];

p_{Dk} : number of k^{th} type lost formwork components that remain built-in or formwork components “consumed” in construction [pc];

c_k : the price of one formwork component of the k^{th} type [EUR. pc^{-1}];

f_k : a coefficient expressing the cost of renting (depreciation) from the cost of a formwork component of the k^{th} type per unit of time [$days^{-1}$];

T_F : the term of the formwork removal from the last zone [date];

T_S : the term of the formwork components' delivery to the site, i.e., planned starting term of the formwork mounting in the first zone [date].

Due to the large variability of inputs to tasks of large-scale constructions, the task solution often consists of targeted experimentation through software applications based on input changing. In the case of large-scale constructions, the parallel use of full or partial formwork in several uneven zones is common. A demonstration of the summarizing result in the case of a selected type of formwork component (formwork boards) is presented in Figure 2. The figure shows the histogram and cumulative charts of mounting and removal of the formwork component of the given type. The formwork boards were used to form the ceiling structures, where concreting was performed in six zones. The partial release of the formwork components from zones (concreting boards and beams) was made on the 14th day after concreting, and supporting elements (supports) were removed after the next 14 days.

Some of the concreting boards remained in the zone after partial removal of the formwork, and a part of the boards in the amount $p_{Dk} = 55$ [pcs] was “consumed” during construction, i.e., the cost of the boards renting is not included in the cost of the formwork, but the price of the boards is involved. The renting cost of $(p_{kmax} - p_{Dk}) = (275 - 55) = 220$ [pcs] boards were considered for the interval from (TS) 15.4.2010 to (TF) 22.9.2010, i.e., from the term of their delivery to the site and their installation in the first zone to their removal from the last zone.

The software-based processing of the designed model presents the basic condition for its practical use to harmonize the construction conditions to optimize the number of formwork components and to minimize the cost of the formwork.

The methodology of summarization of the formwork components and the algorithm for the determination of the formwork cost is incorporated into flowchart presented in Figure 3a,b.

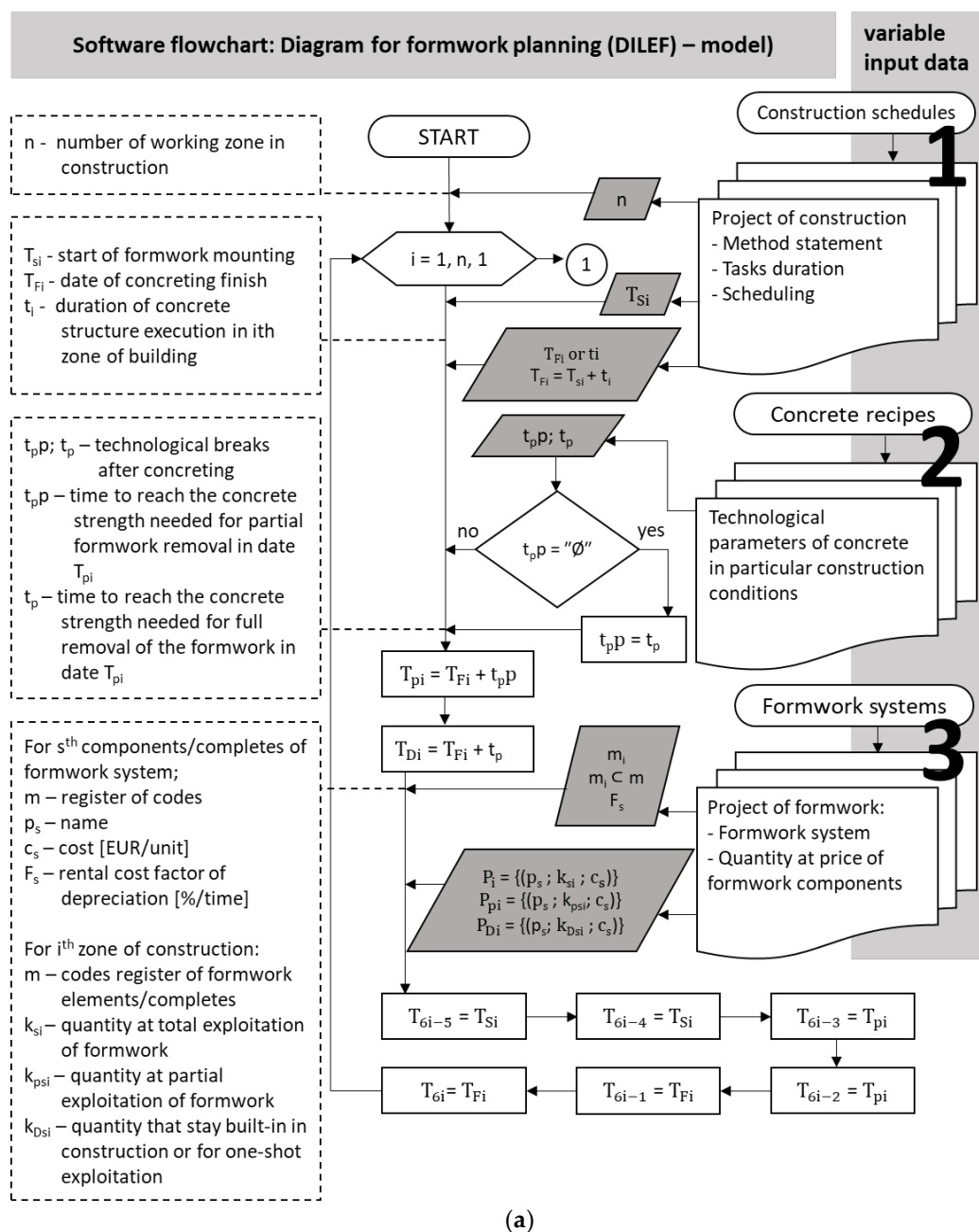


Figure 3. Cont.

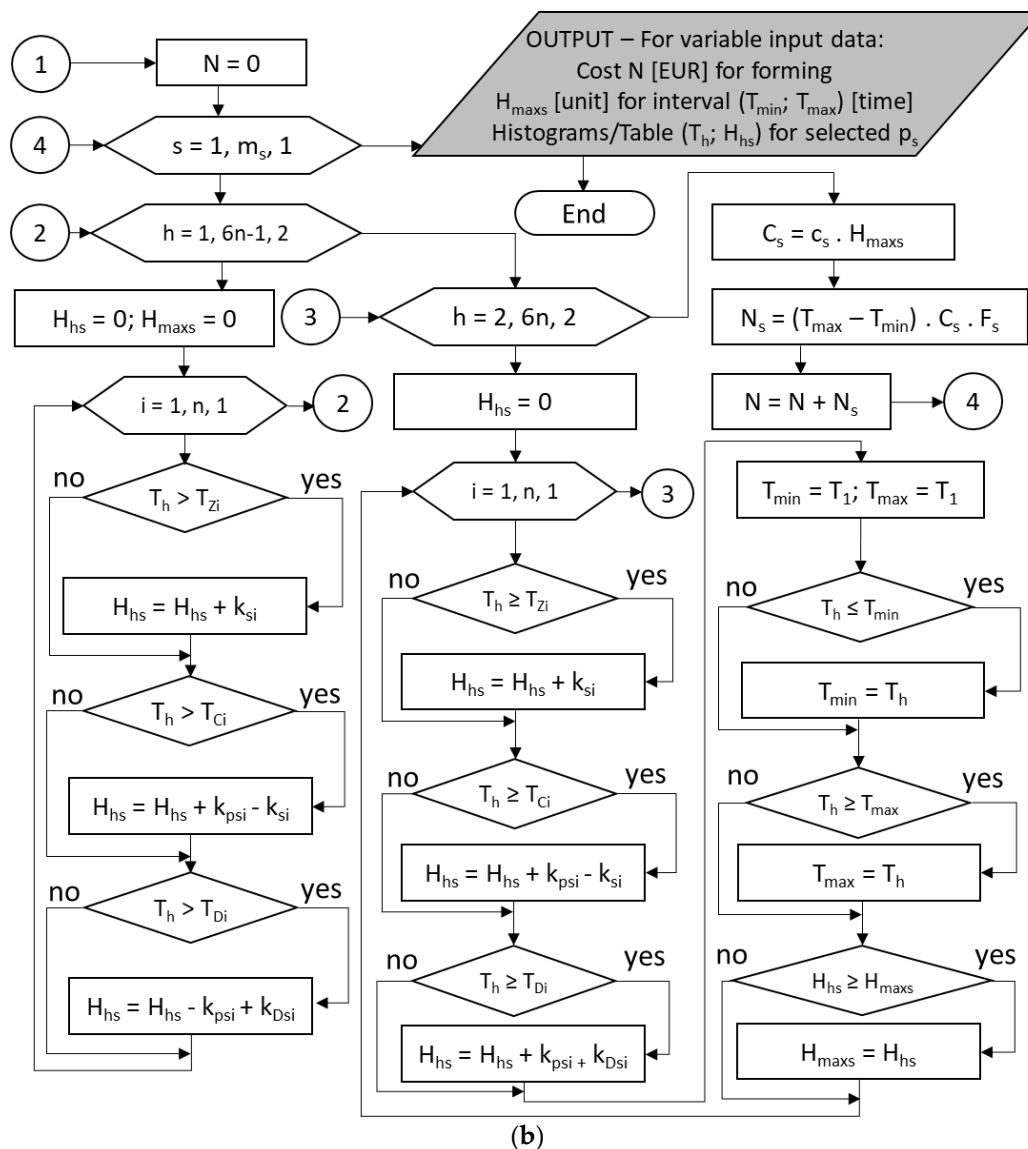


Figure 3. (a). The flowchart for DILEF (diagram for levelling a formwork)—the dynamic model for summarization and determination of the formwork cost—part I. (b). The flowchart for DILEF (diagram for levelling a formwork)—the dynamic model for summarization and determination of the formwork cost—part II.

The outputs from the dynamic modelling of the formwork use are intended for the (i) adjustment of construction schedule to reduce the total costs for formwork; (ii) selection of formwork optimal type for construction; (iii) optimal number specification of formwork elements or completes and specification of optimal reusing and formwork deployment for construction and a given construction schedule (minimization of costs for depreciation or rental of elements); (iv) specification (minimization) of costs for montage or removal of temporary construction and for creation of building site; and (v) specification of optimal technological parameters of concrete, etc.

3.2. Case Study

An administrative building was chosen to solve a specific example. From a structural point of view, this property is a triple-element concrete monolithic system (slabs, beams, and columns). The building has five floors above ground and one underground. All floors

have the same ground plan. In order to solve this problem, the formwork for horizontal structures, such as beams and slabs, is taken into consideration (Figure 4).



Figure 4. The administrative building.

For a specific example, six variants of a solution were proposed. Variants differ in various user inputs from the schedule or different specified technological breaks for the striking of the slab structures. In the example, all variants used the same type of system formwork.

(A) variants of schedules:

- i. one working zone = one floor (longer construction period, but concreting of ceiling is achieved without interruption);
- ii. one working zone = half of a floor (shorter construction period but should be addressed as an interruption of the concreting of the ceiling board).

(B) variants of technological breaks:

- i. formwork is removed from the working zone 28 days after completion of the concreting of the ceiling slab;
- ii. partial removal of formwork from the working zone is scheduled 14 days after completion of the concreting of the ceiling slab, and complete removal of formwork is scheduled 28 days after;
- iii. partial removal of formwork from the working zone is scheduled 7 days after completion of the concreting of the ceiling slab and complete removal of formwork is scheduled 14 days after (predicted an increased cost of concrete with rapid resuming of strength or editing of concrete-hardening conditions on site).

(C) For a specific site, a developed drawing of formwork of the typical floor was developed with two alternatives: drawing of the formwork for full load (Figure 5) and drawing of the formwork for partial load (for formwork after partial stripping). These formwork drawings were processed using the software Tipos 4.0.

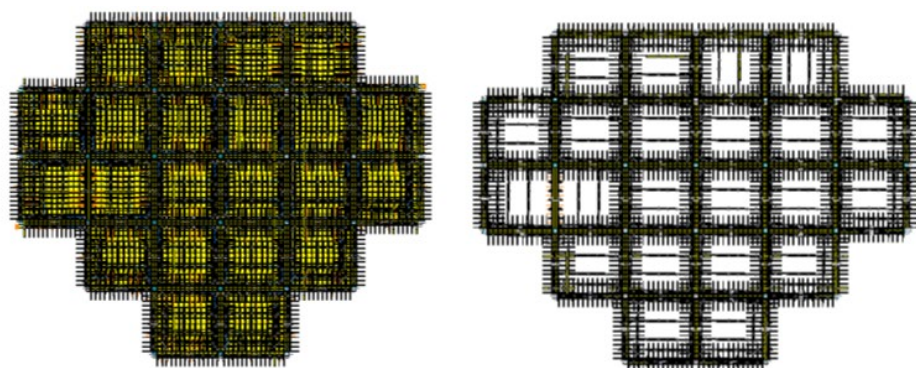


Figure 5. Drawings of the formwork of one typical floor for full load (on the left) and for partial load (on the right).

Definition of the variants:

VARIANT I: combination of (A) i. and (B) i.

VARIANT II: combination of (A) i. and (B) ii.

VARIANT III: combination of (A) ii and (B) ii.

VARIANT IV: combination of (A) ii and (B) i.

VARIANT V: combination of (A) i and (B) iii.

VARIANT VI: combination of (A) ii and (B) iii.

The results of the comparison of the variants in terms of the formwork cost are presented in Figure 6.

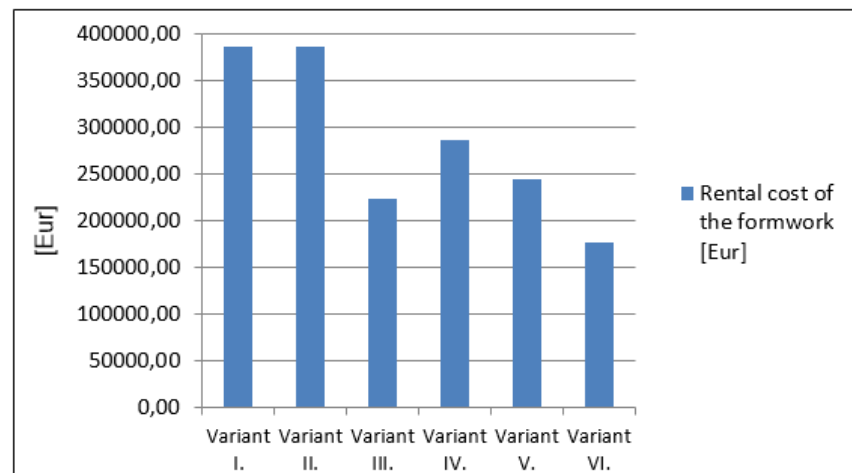


Figure 6. The results of the variants comparison in terms of the formwork costs.

The software tool developed based on the mathematical method of dynamic modelling provides automated determination of formwork cost, as well as generation of summation charts or histograms of selected components/sets of the formwork for variant inputs into modelling.

The modelling inputs, entered into the software developed based on the computational algorithm of the dynamic model, are as follows:

- i. an item code (corporate catalogue number of the component of formwork system);
- ii. color resolution of the formwork components in generated histograms and cumulative charts;
- iii. measurement units (pc, m², set, etc.) and a price per unit of amount;
- iv. terms of mounting start and terms of concreting finish for different construction zones (eventually the term of concreting finish is calculated when entering the durations of the partial construction processes in zones);
- v. amounts of each type of the formwork component; (from plan of formwork);
- vi. duration of technological breaks after concreting;
- vii. amount of formwork components remaining in the zone after technological breaks finish (entered in “percent” or in the relevant measurement unit).

A demonstration of the environment of the software for the representation of the input parameters (histogram—time course of the formwork components used in construction and cumulative curves for formwork mounting and removal) is presented in Figure 7.

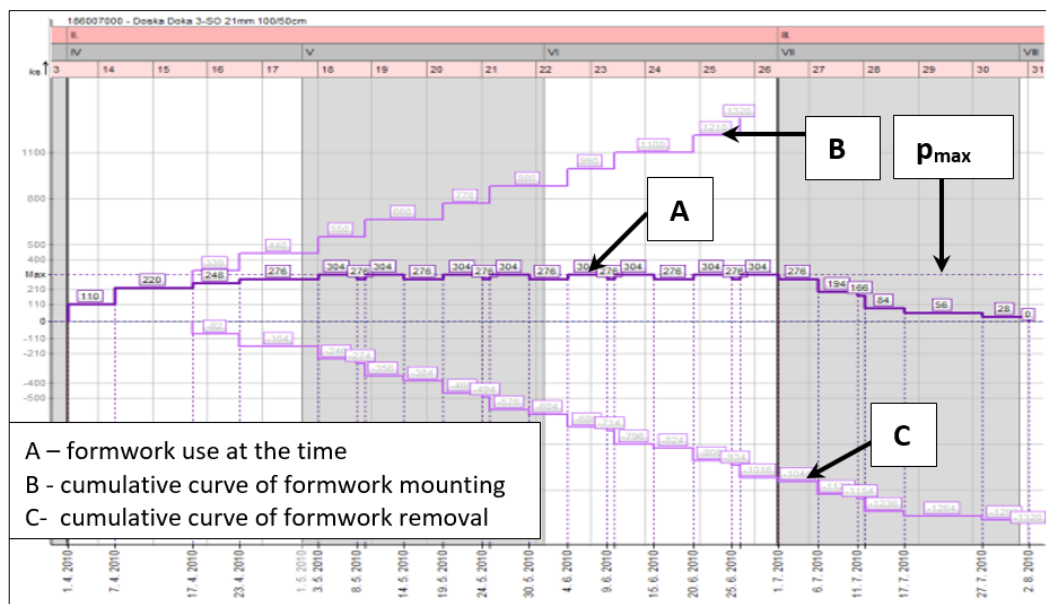


Figure 7. Histogram of the formwork components generated by DILEF software.

When changing any input parameter, the results of the formwork components' summarization are automatically recalculated.

In one chart, a histogram for one selected type of formwork component or for more types in parallel is displayed. It is possible to hide or reveal the cumulative charts. Figure 8 presents the generated histogram for two selected types of the formwork components (ceiling boards and beams H20 P 3.90 m).

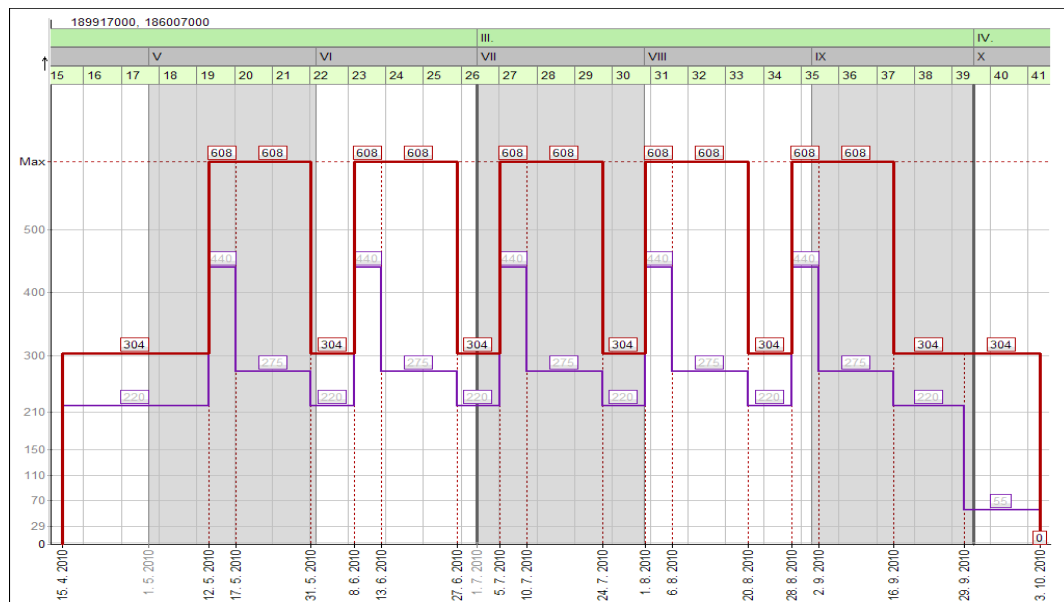


Figure 8. The parallel presentation of histograms for two selected types of formwork components.

The software application of dynamic modeling facilitates the examination and selection of an optimal variant of formwork deployment in the intended construction schedule. It also allows examination and changes in the external conditions or technological parameters of concrete; eventually, changes in the formwork system affect the construction schedule or the formwork cost, etc.

The graphical comparison of the results of the summarization of the formwork components for variable inputs into modeling is presented in Figure 9. The results of the

summarization of the same component after changes in the construction schedule are presented in two horizontally nearby figures. The demonstrations of the effect of changes in technological break duration on the necessary amount of formwork components is presented in vertically nearby figures. The change in technological break duration was entered for partial and complete removal of formwork from the zones. When changing the inputs, the formwork cost is automatically recalculated. A set of inputs predestining optimal use of the formwork in construction is sought based on the modeling through simulations. The problem of determining the stability of optimal tasks solution aims to find out how a change in the input conditions affects the optimal solution of the task; eventually, the extent to which a change is permissible in terms of the achieved optimal solution is affected.

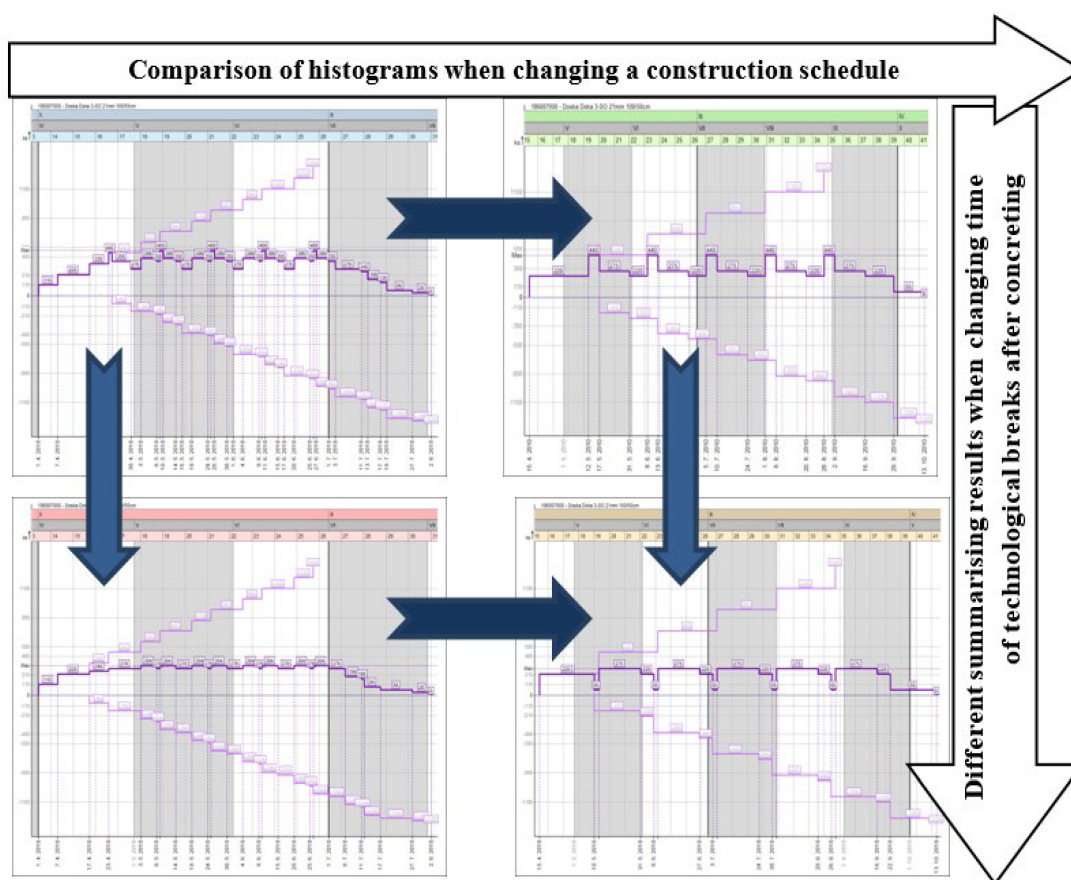


Figure 9. The results of summarization of the formwork components for variable inputs into modelling.

The procedures and methods to investigate the impact of changes in the task conditions on the resulting optimal solution can be divided into two groups:

- i. Discreet analysis of sensitivity: if the specified input values of a task within a certain interval are changed so that the optimal solution is not changed, i.e., proposed optimal amount of formwork components etc., but only the value of the purpose function is changed (the cost of the formwork is changed);
- ii. Parametric modeling: if the values of the task inputs are changed depending on one or more explicitly specified parameters.

The comparison of benefits of variant solutions, obtained via software-based modeling or the simulation of different inputs, is a basis for optimal decision making. Moreover, the dynamic model is effective for analysis of the benefits of deployment of other auxiliary structures (scaffoldings, sheeting, etc.) that are only temporarily available at the site and are intended for multiple uses.

The indicator of optimality may be the percentage expression of the ratio between the eligible costs for formwork for the input modelling conditions and the theoretical costs, calculated by assuming that the elements are located at the construction site only at the time when the formwork transfers the load from the construction. Graphically, we can determine the optimal degree of variants using histograms of the formwork element. In this case, we compare the ratio of areas of eligible costs (areas created by a horizontal axis and the line p_{\max} (Figure 7)) and the theoretical costs (area created by a horizontal axis and curve A (Figure 7)), considering the price of the formwork elements. The mathematical relationship is as follows:

$$E = \frac{C_F + \sum_{i=1}^z \sum_{k=1}^S (p_{ki} \times t_{ki} \times c_k \times f_k)}{C_F + \sum_{k=1}^S ((p_{k\max} - p_{Dk}) \times (T_F - T_S) \times c_k \times f_k)} \times 100 \quad [\%] \quad (7)$$

where

z : number of working zones of monolithic reinforced structure of object/construction;

S : number of formwork components type, such as concrete slabs, beams, retaining and supporting elements or systems, sets of formwork columns, working platforms, etc.;

E : percentage expression of the extent to which the estimated cost for formwork for the input conditions of modelling nearing to the required optimum [%] (optimal solution is if $E_{opt} = 100\%$);

p_{ki} : number of formwork elements of the k^{th} type in the i^{th} working zone [pc];

t_{ki} : total time of deployment of the formwork elements of the k^{th} type in the i^{th} working zone [days];

c_k : price of the one formwork element k^{th} type [EUR. pc^{-1}];

f_k : coefficient that represents the relative number of rental costs (depreciation) for the unit of time from the price of element of the k^{th} type [day^{-1}];

$p_{k\max}$: number of formwork elements of the k^{th} type, located on the construction site [pc];

p_{Dk} : number of formwork built-in elements of the k^{th} type, which are consumed on the construction site [pc],

T_F : date of release of formwork from the construction site after removal from the last working zone [date];

T_S : delivery date of the formwork elements to the construction site, i.e., planned start date of formwork installation in the first working zone of the structure [date];

C_F : fixed costs of the formwork elements of the working zone/structure, i.e., price of p_{Dk} formwork elements and the price of consumables, components, and products that are a part of the formwork [EUR].

When modeling the formwork, we focus on the main parameters, such as the choice of the type of formwork, the load-bearing capacity of the formwork, the type of future structure, requirements for the surface of the concrete structure, etc. However, the optimization of the formwork also includes the performance of basic boundary conditions required by legislation, which was established at the beginning of the research.

The boundary conditions for formwork design optimization include the following: the human factor; the durability and quality of the formwork; and external factors (e.g., weather conditions and seasonal variations). As for the human factor, formwork can only be assembled by a crew of specially trained workers under the guidance of a specialized foreman. In the case of failure of the working crew, it is necessary to have another relevant crew in reserve, which will ensure work with the formwork. The durability and quality of the formwork is ensured by emphasis on the procurement of formwork material only from certified formwork system manufacturers. External factors, such as weather conditions and seasonal variations, are almost unpredictable and often beyond our control. It is possible to plan the implementation of rough construction in suitable months when weather changes are not expected or are only minimal. It is also possible to implement measures, e.g., a construction site tent above the constructed structure. Increased costs due to the

weather occur mainly at higher altitudes, during dry and hot summer seasons, and during catastrophic events (wind, flood, snow, etc.). These are unforeseeable events, risks for which we can prepare with a solution plan (project management for risk management), which defines measures for further action if such cases occur.

4. Discussion

It is characteristic of a construction model that most parameters are static, while the characteristics of construction process models are often dynamic parameters, as the model imitates the possibility of changes in the conditions of the process implementation in time and space and their impact on its progress. In construction projects, using modeling and by experimenting with various systems models, it is possible to design a solution that yields minimal costs while maintaining the required quality and construction time, together with considering the optimal use of production capacities. Simulation methods are used to solve complex problems, where the complexity of the simultaneous action of a number of factors makes it difficult to use simpler optimization methods. To use computer simulation in a construction project, it is necessary to create a real or almost-real dynamic model of the modeled system. The core of the model is a simulation that provides a combination of input variable values to generate possible outcomes. It is necessary to realize that simulation is not a path that will always yield an optimal solution. Rather, it is a supporting tool that helps designers test the effects of their decisions on a simulation model and to detect errors in the construction project even before its implementation. Essentially, a computer simulation is a “trial construction project” in a digital form that helps verify the effects of various design solutions and management strategies. Currently, there are also other reasons for applying simulation techniques in a construction project. The adoption of ICT-based simulation is facilitated by the rapid development in the area of computer technology and software. High availability of BIM-based tools, new simulation methods and tools, and the explosion of information, products, and technologies are a sign of the Fourth Industrial Revolution. Analytical handling, with the task of minimizing formwork elements’ cost in construction multi-story or extensive buildings with uneven and often simultaneous deployment of formwork in individual building zones, can be difficult and thus less suitable. In such cases, rather, a numerical solution is applied, where the results of the variant proposals obtained by ICT-based simulations are evaluated. When adjusting the construction schedule in terms of the deployment and utilization of construction resources, various optimization methods of scheduling or balancing the need for resources are used. Adjusting the construction schedule in terms of deploying the formwork in construction is one of areas of resource optimizing. The results from the resources’ summarization are the basis of resource optimization. The representation of such results in the form of histograms yield better orientation in the analysis, subsequently adjusting the optimal construction schedule. While in the case of labor and material resources, time-planning software offers tools to summarize them, this does not apply to the generation of histograms of elements or sets of auxiliary structures to which the formwork belongs. The proposed methodology for the summarization of formwork elements and its processing, with the help of software, represents one of the tools necessary for ICT-based experimentation with variably entered inputs to the modeling of formwork deployment and necessary to evaluate the optimality of the variants obtained by simulations. The basic mathematical algorithm of the dynamic model used to summarize and calculate the costs of the formwork elements presented in the paper considers inputs from the construction schedule and from the formwork plan. It also considers the technological properties of concrete in specific construction conditions. Solving the tasks of the optimal deployment of formwork in a construction project can be aimed at several sub-goals: choose the optimal type/system of formwork; maximize the reuse of formwork elements and minimize the amount and cost of elements for a group of concrete structures within the scope of a working zone or the entire construction; minimize the time of deployment of formwork elements in zones and the total time of their deployment on the project; and optimize the organization of work on the construction

site with regard to the available amount of formwork, etc. The mentioned methods of reducing formwork costs influence each other and several are closely related. For example, the selection of a suitable formwork system has an impact on its element composition in the construction zones and on the work difficulty of the assembly and disassembly of the formwork, etc. Some optimization tasks can be solved using analytical methods, while others are more suitable to be solved using simulations. For example, solving the task of optimizing construction costs of the rental/purchase of formwork, which belongs to the area of dynamic programming, can be difficult even with the use of ICT. If formwork can be implemented in several technically and technologically realistic variants, the search for the optimal solution can be quite labor-intensive.

5. Conclusions

In construction practices in Slovakia, formwork planning is often missing, and its selection is based only on previous experience. In the experimental modeling of the formwork deployment, answers to various questions are sought:

- i. How many formwork components are necessary for the execution of construction?
- ii. What is the components/sets' optimal turning rate for different construction times?
- iii. How does the cost of the formwork change in terms of dependence on construction time?
- iv. Is it better to buy or rent the formwork components?
- v. How will the modification of technological parameters of ready-mix concrete be reflected in the cost of the formwork?

The input information is inevitable for obtaining answers. The plan of the formwork presents an essential basis for obtaining the task solution. The formwork composing drawings are prepared in the formwork plan, i.e., a report of the formwork components for temporary use in various construction zones. The report should be supplemented by information on the prices of the components, as well as the cost associated with their rent. Moreover, the evaluation process includes information on the cost of transport of the formwork to the construction site. The right choice of formwork type and the not overequipped composition of the formwork components in the construction zones present the basis for the optimal planning of the formwork. The composition of the formwork components should be harmonized so that the maximum number of the components can be repeatedly used in all construction zones where multiple uses of the formwork components are relevant. The optimal solution of the tasks related to formwork use considers not only the plan of the formwork, but also inputs from the construction schedule and technological properties of concrete in real construction conditions. The mathematical basis for solving optimization tasks of formwork deploying in construction using analytical or numerical methods through the simulations presented in the paper does not have the ambition to replace the expert approach of specialized companies focused on the design of formwork. The ambition is to draw attention to the time factor, which significantly affects the economy of formwork on each construction project. The solution to the task of optimizing the formwork costs aims to eliminate the time when the formwork elements are on the construction site longer than is necessary in terms of the acquisition of concrete strength. The developed methodology to summarize the formwork elements and its software support represent a high-quality input for mathematical modeling of several indicators of the effectiveness of the formwork used on construction projects. For example, a proportional or percentage expression of the extent to which the proposed number of working zones/building zones, together with the proposed composition of formwork elements (when the formwork is gradually deployed in the working zones/building zones) or the proposed reuse rate of the formwork elements for a given construction schedule, etc., comes closer to the required optimum and draws attention to hidden reserves in the optimization tasks if the calculated or computer-generated numerical value of the indicator is lower than 1 or 100%.

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