Combinatorial Method of Computer-Assisted Multiversion Design of Construction Operations

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Abstract. A combinatorial approach to the automated design of construction processes on the variant basis is reviewed in this article. The essence of the approach is in the automated formation of a complete set of all feasible planning and technical solutions for construction works at each design stage based on the capabilities of the construction and installation contractor, working conditions, the characteristics of the construction facility, followed by selection of the best solution according to specified criteria. Choosing of the best option for the construction process implementation occurs after the completion of the full range of formation of technological and planning solutions for each of the alternatives allowing full use of system approach in designing of the construction operations. A combinatorial approach based on the analysis procedures (in fact, building a decision tree for certain stages of design) and synthesis (finding all possible combinations of complex construction production based on the selection of options for the construction of its individual subsystems and elements) is used as a methodological basis for generating alternatives. The choice of the best option of a complex of planning and technical solutions for the implementation of the construction process is carried out at the final stage, which allows to implement the system technical approach to the design of construction systems to the greatest extent [1], since each alternative solution of each stage of the design of the construction production is estimated in terms of its impact on all the fundamental parameters of the system – the duration of the construction process and indicators of uniformity of resource usage within the schedule, the cost of the construction of the object, the parameters of the site organization within the construction master plan, the intensity of the process, etc.

1. Introduction
In the design of the construction operations at different levels and stages of the process, as a rule, there are alternative options for making planning and technical solutions. The choice of a solution is rarely determined by clearly defined criteria for certain conditions of its implementation. The choice of the preferred alternative solutions is often made on the basis of the subjective opinion of design specialists without careful consideration of alternatives. We are talking about alternative technologies for the production of construction and installation works, options for the formation of sets of construction machines and teams of construction workers, possible schemes of spatial division of the construction object into grips (plots, etc.), alternative calendar models of construction processes and other planning issues, assuming the possibility of alternative solutions.
The current practice of designing of construction operations practically does not involve variant study of solutions – in most cases a certain combination of solutions is formed at each level, which corresponds to the conditions, restrictions, typical technological maps. Variability of study is present in the minimum volume, for example, the selection of alternative sets of construction machines, their comparison and selection of the best option.

At the same time, there is a direction in the area of management and planning, which was developed from a long time ago formulated and widely used methods of morphological analysis, which was named "the combinatorial approach" [2]. The essence of the combinatorial approach is that for each feature of the object, as well as in the morphological method, they make lists of the variants; after that, a complete search of all possible matching (combinations) of feature values is performed. Thus, in respect of the design of construction production, the combinatorial approach should come to the generation of all feasible planning and technical solutions (PTS) for the production of construction works and consideration of their possible combinations.

At the same time, the advantages of the combinatorial approach in the above understanding of this term are obvious in relation to the design of construction production – when generating all feasible options for the implementation of construction production, it becomes easier not to miss the "best" option or combination. Given that in the traditional approach to the design a specialist usually forms a combination of solutions, which may initially be not the best, which in case of non-compliance with the established conditions and restrictions, he begins to optimize (for example, to increase the amount of resources or the degree of combining of processes to reduce the duration of construction, to replace some technologies with others in order to intensify the process, etc.). But there are also obvious disadvantages of the combinatorial approach – the number of alternative options for the implementation of the construction process can be extremely large (from several thousand to millions and billions), which makes it impossible to evaluate each of the options by a specialist and this imposes special conditions for the implementation of the combinatorial approach. The first thing is the unconditional use of computer technology and related algorithms of design automation (of course, that specialist is not able to form, to make a comprehensive study and to compare "manually" even tens of alternative options of construction), and the second thing: the algorithms must ensure the isolation of variants of implementation of the construction process that may be possible, but do not meet building practices, standards, common sense, etc.

2. Results of Application of Combinatorial Approach to Automated Design of Construction Processes on the Variant Basis

Design of construction production involves the solution of a set of interrelated tasks:

1) Formation of planning and technical solutions at the level of simple technological processes (defining of the range and scope of work, choice of standard operating procedures, selection of construction machines and mechanisms, determining the composition and calculation of the need for organizational and technological resources, the formation of technological schemes of work);

2) Forming up of a calendar model of construction production, including schedules of resource movement (workers and machines), needs and delivery of construction materials and structures;

3) Formation of the construction master plan (planning of the construction site infrastructure, calculation of the need for temporary buildings and structures, electricity, water, storage areas, etc.).

On each of the above stages of building production design it is proposed the implementation of a combinatorial approach: either within the framework of the analysis, the formation of the set of all feasible solutions, or, in the framework of the synthesis, the determination of all possible combinations of solutions generated in the previous step.

Thus, at the level of generation of solutions for the implementation of simple technological processes, alternative technologies for their implementation are determined, for each technology, alternative options for their implementation are formed in terms of possible combinations of the use of available planning and technological resources (in terms of brigades staff, construction machines) (the analysis procedure is implemented within the combinatorial approach). The final result of the variant
formation of planning and technological solutions at the level of simple technological processes is a set of all feasible solutions for their implementation with a certain composition of organizational and technological resources (working, construction machines and mechanisms, building materials, structures and products), with calculated intensity, duration and direct costs of work.

At the level of formation of integrated construction processes, options are generated by determining all possible combinations of alternative options for the implementation of simple technological processes (the synthesis procedure is implemented within the combinatorial approach).

At the level of calendar modeling for each combination of the complex process, alternative variants of calendar model are formed by considering various schemes of combining construction processes, shift-working arrangements (the analysis procedure is implemented within the combinatorial approach) and the calculation of schedule of work for each option is performed.

Next, the options for the production of construction works are compared according to the criteria of duration, cost, and the best option is selected.

At the final stage, a set of output documentation is formed for the selected best option (bill of quantities, bill of needs and delivery of organizational and technological resources, schedule of works, construction master plan).

The schematic diagram of the implementation of the combinatorial approach in the design of construction production is shown in figure 1.

Figure 1. The schematic diagram of the implementation of the combinatorial approach in the automated variant design of construction production.
Depending on participation of different types of organizational and technological resources in the construction process (workers, construction machines) different types of technological processes are emphasized: non-mechanized (involving only workers), fully mechanized (involving only construction machines), mechanized (involving both workers and construction machines) [3].

In the framework of this article, we present an algorithm for automated formation of organizational and technological solutions only for mechanized processes (with participation in the technological process of both construction machines and workers).

At the initial stage, the composition of the construction machines planned for use (similar to the above procedure for fully mechanized processes) is determined, and then - the number of workers, taking into account the need to ensure coordinated functioning of machines and workers. To prevent operational downtime of construction machines and workers due to the backlog in the performance of the relevant technological operations either by machines or by workers, the equal intensity of their work is provided by executing the following expression:

\[ N = \frac{P_M}{P_R} = P_M \times H_T \]  

Where:

\[ P_M \] - the total working capacity of construction machines for the corresponding version of the technological process fulfillment:

\[ P_M = P_1 + P_2 + \ldots + P_n \]  

\[ H_T \] - work time expenditure for this production process.

\[ P_R \] - productivity of one worker.

Since the number value obtained by the expression (1) can be rounded up to an integer value both in the larger and in the smaller direction, the result is two variants of the formation of the technological system "machine(s)-workers" – with rounding up (corresponds to the downtime of workers) and rounding down (corresponds to the downtime of machines).

Both of these options can be taken in the organizational and technological design as alternative planning and technical solutions for the implementation of a simple technical process.

The speed of creation of construction products of the mechanized process (with the participation of construction machines and workers) is determined relying on the comparison of aggregate productivity of workers with the total working capacity of construction machines. Herewith, the value of the speed (intensity) of the execution of work is calculated by the lowest of the values of the working capacity of machines or aggregate productivity of workers [3]:

\[ \frac{N}{H_T} - P_M > 0 \Rightarrow I = P_M \]

\[ \frac{N}{H_T} - P_M < 0 \Rightarrow I = \frac{N}{H_T} \]

\[ \frac{N}{H_T} - P_M = 0 \Rightarrow I = \frac{N}{H_T} = P_M \]  

Where:

\[ I \] - intensity of production of construction and installation works for the mechanized process.

\[ P_M \] - total working capacity of construction machines.

\[ N \] - number of workers;

\[ H_T \] - time expenditure for labor costs of a unit volume of works;

\[ N/H_T \] - aggregate productivity of workers.
The duration of the technological process is calculated (in hours) as follows:

\[ T_{ij} = \frac{V_i}{I_{ij}}, \]  

(4)

\( V_i \) – scope of work for the i-th technological process;
\( I_{ij} \) – the intensity of work performance for the j-th variant of planning and technical solutions for implementation of the i-th technological process;

To calculate the direct costs based on time-based rates, it is proposed to use the following expression:

\[ C = T\left(\sum_{i=1}^{n} C_{p_i} N_i + \sum_{j=1}^{k} C_{M_j} k_j\right) + m_k C_{mk} V \]  

(5)

Where:
\( C_{p_i} \) – a cost of a man/hour of a specialist’s work of the i-th specialty and category;
\( N_i \) – the number of workers for the i-th specialty and category;
\( C_{M_j} \) – a cost of one machine/hour for the machine of j-type;
\( k_j \) – quantity of simultaneously working construction machines of j-type;
\( m_k \) – expenditure rate for the k-material, construction or product;
\( C_{mk} \) – cost of a unit of the k-material, construction or product;
\( V \) – scope of work for the relevant technological process;
\( T \) – duration of execution of work.

In order to determine the cost of construction and installation works on the basis of unit prices, it is possible to use the following expression:

\[ C = C_{p_i} \times V_i + C_{M_j} \times V_i + m_k C_{mk} V, \]  

(6)

\( C_{p_i} \) – statement of labor cost of workers for the unit volume of work for the i-th process;
\( C_{M_j} \) – statement of the cost of machine operation for the unit volume of work for the i-th process.

Figure 2 shows the algorithm of automated generation of planning and technical solutions for mechanized technological process (construction machines and workers are involved).

On the basis of the above methodology the automated design system will generate alternative versions of performance of work at the level of simple technological processes. Obviously, it is possible to implement only one of the alternatives for each simple technological process.

Generation of options for fulfilling of the integrated process is based on complete search of possible variants of the planning and technical solutions for the simple technological processes, composing an integrated process.

The search of variants of fulfillment of simple technological processes for the generation of options for the implementation of an integrated technological process can be carried out in the form of a matrix of search, which is shown in Table 1 below (the following process parameters are used in the example: the number of components of simple technological processes - 3, the number of options for planning and technical solutions for each simple technological process - 2):

- process 1 - implementation alternatives 1.1 and 1.2;
- process 2 - implementation alternatives 2.1 and 2.2;
- process 3 - implementation alternatives 3.1 and 3.2.

The above variant numbers (1.1, 1.2, 2.1, 2.2, 3.1, 3.2) are unique identifiers of the alternative planning and technical solutions generated by the computer program which are characterized by a certain technology of performance of works, structure of the resources supposed to use, intensity, duration and direct expenses for performance of works.
Figure 2. Algorithm of automated PTS generation for the mechanized technological processes.

Table 1. Matrix of searching.

| Variants of integrated technological process | Process 1 | Process 2 | Process 3 |
|--------------------------------------------|-----------|-----------|-----------|
| 1                                          | 1.1       | 2.1       | 3.1       |
| 2                                          | 1.2       | 2.1       | 3.1       |
| 3                                          | 1.1       | 2.2       | 3.1       |
| 4                                          | 1.2       | 2.2       | 3.1       |
| 5                                          | 1.1       | 2.1       | 3.2       |
| 6                                          | 1.2       | 2.1       | 3.2       |
| 7                                          | 1.1       | 2.2       | 3.2       |
| 8                                          | 1.2       | 2.2       | 3.2       |

For each alternative variant of implementation of the complex process (in the above example there are 8 different combinations) it is possible to determine all the necessary organizational and technological parameters: intensity, duration, cost, labor intensity, etc. of construction works on the
basis of summing the values of the parameters for the solutions corresponding to the unique identifiers.

Particularity of the use of a combinatorial approach to the generation of options for the planning and technical solutions for production of construction works lies in the fact that a sufficiently large number of alternatives to the implementation of the construction process are formed. For example, when the construction of a monolithic reinforced concrete structure involves three main works: reinforcement, formwork and concrete, it is possible to implement three different technologies for each of the types of work, and within each of the technologies 5 combinations of the use of available resources are possible, then the total number of options will be equal to: \((3*5)*(3*5)*(3*5) = 3375\) options. For most projects, the number of construction works, options for their fulfillment and final alternatives for the implementation of construction production is way more than in the presented tentative example. It is clear that it is impossible to generate the calendar patterns for each of the 3375 variants of implementation of the construction process manually, by setting the parameters of alignment, shift, etc. To be able to implement the combinatorial approach to the full extent (at all major levels of organizational and technological planning: the generation of alternative solutions at the level of simple processes, the formation of combinations of implementation of options for simple processes within complex and integrated processes, as well as scheduling) it is required the development of an algorithm for automated scheduling for the entire complex of alternatives.

The advantage of this approach to time scheduling is that the paradigm of solving the problem is changing: from the optimization of the schedule for a single set of solutions for the production of construction works, that perhaps initially are not the most effective among the possible, to generation of all possible variants of calendar models and the choice of the most preferred. Under this approach, there is more likely not to "miss" the best option of the planning and technical solution for production of works.

Of course there are certain algorithms for the automated generation of time schedule, and they have been studied deep enough. At the same time, there are no scheduling algorithms on the variant basis, which makes this task quite relevant from a scientific and applicative point of view within the combinatorial approach.

The essence of the task is that the algorithm of scheduling for each of the combinations of the planning and technical solution for production of works should form variants of calendar models, which cover all possible combinations of processes, shifts, etc., and taking into account the specified parameters of technological and organizational relationships between the processes.

The schematic diagram of the formation of the calendar model of construction production on a variant basis is shown in Fig. 3.
The proposed approach, of course, requires detailed study and formation of the algorithm of multiversion scheduling. The main essence of the algorithm should consist, again, in the use of a combinatorial approach, when while forming variants of the calendar model, the computer program will take all possible combinations of decisions on the arrangement of joint execution of processes - in terms of combining in time, shift, schemes of spatial division of the construction object, the sequence of development of processes on grips.

Within the framework of conducted study, a vector method was chosen from a possible variety of models for quantitative assessment (formation of an integral indicator), as well as for the comparison and selection of the best option [4], which is also very convenient in terms of visual representation of alternative options for the construction process and their comparison with each other.

Vector model for 2-criteria problem (it is proposed to use the duration and cost of construction as criteria for the evaluation and selection of the best option) is written as:

$$V_i = \sqrt{T_i^2 + C_i^2}$$

Fig. 3. Schematic diagram of the formation of the calendar model of construction production on a variant basis.
\[ T'_i = \frac{T_i}{T_{cp}}, \quad C'_i = \frac{C_i}{C_{cp}} \]  

(8)

Where \( T' \) and \( C' \) - the normalized (corrected to a comparable form) values of the evaluation criteria of options for the implementation of the construction process.

3. References

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