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IDENTIFCATION OF WEATHER INSENSITIVE TO CONSTRUCTION SCHEDULES

IDENTYFIKACJA HARMONOGRAMU BUDOWLANEGO NIEWRAŻLIWEGO NA POGODĘ

A b s t r a c t

Construction scheduling deals with the decisions which can affect the feasible sequence of construction activities, the selection of alternative execution modes for the activities and the positioning of the construction in time. Effects of these decisions can be evaluated by means of specific schedule evaluation criteria. However, the peculiarity of construction in civil engineering causes that the real effects of the construction also depend on the influence of the surrounding environment. For example, construction processes are sensitive to adverse weather. Poor weather influences the actual performance of construction activities. The performance of the activities influences the performance of the whole construction project. Thus, the performance of whole construction project is also influenced by bad weather. Considering the influence of adverse weather is therefore indispensable when preparing a reliable construction schedule. Note, that the effects of poor weather on actual construction performance can be limited by the careful choice of the activity sequence, construction time lines, and the execution modes for various activities. The approach is presented, in this paper therefore provides the appropriate sequence of construction activities, related starting date and the allocation of execution modes to the activities in order to make construction schedule less sensitive to inclement weather.

Keywords: construction, schedule, optimization, activity, sequence, execution mode, allocation, inclement weather, sensitivity

S t r e s z c z e n i e

Harmonogramowanie przedsięwzięcia polega na wyborze właściwej kolejności wykonania prac budowlanych, sposobów wykonania poszczególnych prac oraz umiejscowienia realizacji przedsięwzięcia w czasie. Do oceny efektów tych decyzji są wykorzystywane odpowiednie kryteria, np. planowany czas i koszt wykonania przedsięwzięcia. Zauważmy również, że na skutek specyfiki produkcji budowlanej rzeczywiste rezultaty wykonania przedsięwzięcia zależą od oddziaływania otoczenia. Typowym przykładem niekorzystnego oddziaływania otoczenia są zmienne warunki pogodowe. Wiele rodzajów prac budowlanych (roboty ziemne, betonowe, montażowe itp.) jest wrażliwych na oddziaływanie warunków pogodowych. Niekorzystne warunki wpływają więc na efekty realizacji prac, które wpływają z kolei na rezultaty realizacji całego przedsięwzięcia. Rezultaty te zależą więc również od warunków pogodowych. W trakcie harmonogramowania przedsięwzięcia jest konieczne uwzględnianie niekorzystnego wpływu pogody na efekty realizacji prac i przedsięwzięcia. Zauważmy przy tym, że wpływ niekorzystnej pogody można ograniczać już na etapie harmonogramowania przedsięwzięcia, dobierając właściwą kolejność wykonania prac, odpowiednie sposoby ich wykonania oraz czas rozpoczęcia przedsięwzięcia. W pracy przedstawiono podejście symulacyjne ułatwiające określenie właściwej kolejności realizacji prac i skojarzonej z nią daty rozpoczęcia przedsięwzięcia oraz odpowiedniego przydziału sposobów wykonania operacjom w warunkach niekorzystnego oddziaływania pogody.

Słowa kluczowe: przedsięwzięcie, harmonogram. optymalizacja, prace budowlane, kolejność, sposób wykonania, przydział, niekorzystna pogoda, wrażliwość

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1. Introduction

A construction schedule provides the necessary means for sound construction project implementation. Scheduling deals with the regular decisions that pertain to the selection of the appropriate sequence and execution modes for construction activities, and accurate project time lines. The peculiarity of certain construction processes, however, results in the construction being influenced by conditions caused by the surrounding environment. These possible influences should therefore be included, when preparing the schedule for a construction project.

Many construction processes are weather sensitive. For example, earthworks, concrete-based and assembly processes which are especially sensitive to poor weather. The influence of adverse weather should therefore be properly addressed while scheduling a construction project, in order to provide necessary means for exact and inexpensive project implementation.

The effects of dverse weather and the influence these have on construction processes is a well recognized phenomenon. The optimization of construction projects while considering the possible effects of bad weather is dealt with in the available literature [1–7]. These examples, however, prove that current approaches do not address all regular scheduling decisions. The numerical approach is therefore presented in this paper, which can help to make regular scheduling decisions, while including the inclement weather influence. The approach applies Monte Carlo simulations.

2. The computational model

Let us assume that a construction project deals with the construction works that are represented by m activities: o(1), o(2)…o(m). There are o_i alternative execution modes available for the activity o(i), where: $i = 1, 2 \ldots m$. A single execution mode only can be applied for the execution of an activity. Selection of the j-th execution mode for the execution of the activity o(i) is indicated by the unitary value of the decision variable $x_{ij} = 1$, where: $i = 1, 2 \ldots m$ and $j = 1, 2 \ldots o_i$. The choice of the j-th execution mode results in the regular duration τ_{ij} and cost κ_{ij} for the activity o(i). Decision variables x_{ij} and the regular duration and cost values for all available execution modes constitute the m by $\max_i \{o_i\}$ matrices $\mathbf{x}$, $\boldsymbol{\tau}$, $\boldsymbol{\kappa}$, respectively ($i = 1, 2 \ldots m$).

Construction activities should therefore be executed in a given technological order. In this paper the order is known as the precedence structure. The acyclic, asymmetric and joined digraph representation $\Gamma(V, E)$ is usually applied to express the structure. The digraph arcs E express the activities and digraph vertices V denote the direct precedence relations between the activities. In this paper, the actual feasible sequence of activities are known as project structure, also described by the means of the acyclic, asymmetric and joined digraph $G(V, E)$. This time, however, the vertices represent project events labeled 0, 1…n, where n is at most equal to m. Note, that there are usually a lot of feasible project structures available. The precedence structure and a corresponding feasible project structure are presented in Fig. 1.

The application of execution modes require the following necessary resources – manpower, building equipment and materials. Manpower and equipment are considered as renewable resources because they become available immediately after the completion of an activity, that used them recently. Building materials comprise the non-renewable resources due to the fact that they undergo the continuous consumption during project implementation. Let us observe that fixed construction and material solutions are considered while applying the alternative modes for the execution of activities. It is therefore assumed that all necessary building materials will be available when required.

Note, that execution modes can be expressed by the required renewable resources. It is advantageous, therefore, to consider the availability of the resources in sets. The notion of a technical means set (TMS) is applied in this regard. A given TMS can depend on a less complex TMS. The application of an item of a given TMS makes an item of a component TMS unavailable at the same time, and vice versa.

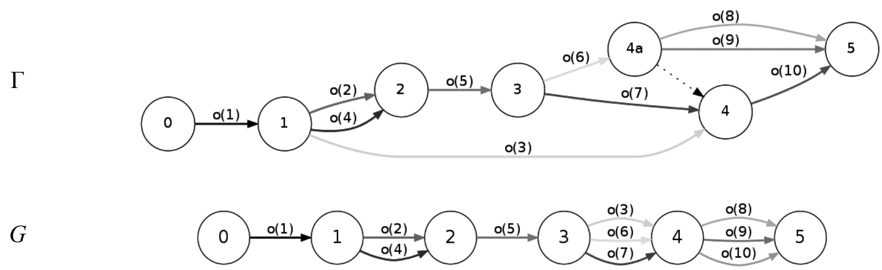


Fig. 1. The sample precedence structure and a corresponding project structure

The peculiarity of construction processes often results in the possibility of using the same renewable resources for the execution of different activities. Necessary resources are usually available in the limited quantities resulting in activities which are executed concurrently competing for common resources. Such the competition deals with the distinct execution modes.

Each possible conflict deals with a specific TMS. The available number of items for that TMS is equal to $L_{l(k)}$. The number of possible conflicts is denoted by Ξ. Note that the number depends on the applied project structure: Ξ(G). The set of execution modes involved in the k-th possible conflict, where k = 1, 2… Ξ, is denoted by $\zeta^{(k)}$. The involved execution modes are expressed by the ordered pairs (i, j), where: i is number of the activity and j denotes the execution mode.

The influence of the weather inclement is expressed by the means of the standard climatic year and the general function of the sensitivity to adverse weather. The standard 365-day-long climatic year does not include February, the 29^{th}. The discrete and binary general function of the sensitivity $\Omega(i, j, k)$ deals with a given execution mode (i, j). It indicates the days of the standard year (k = 1, 2…365) that allow the execution of the activity o(i) while applying the j-th execution mode. The function $\Omega(i, j, k)$ results from the individual sensitivity of an execution mode to inclement weather and the representative weather conditions for the standard climatic year's days [8]. The official recommendations [9] are applied to assess the adverse weather sensitivity. The average hourly data provided by Polish Ministry for Infrastructure and Regional Development (available at the URL: http://www.mir.gov.pl/budownictwo/rynek_budowlany_i_technika/efektywnosc_energetyczna_budynkow/typowe_lata_meteorologiczne/strony/start.aspx) are utilized to define the representative weather data for the standard climatic year's days. The data also corresponds with the location of the construction works. The sample standard climatic year-long profile for a sample general function of the sensitivity is presented in Fig. 2. $\mathbf{\Omega}$ is applied to denote the complete set of general functions of the sensitivity to adverse weather.

It is assumed that an entire working shift is utilized to do construction works. The shift begins at 7 a.m., CET and ends at 5 p.m. The execution of an activity is halted for a whole day if the unacceptable conditions appear during that day. Note, that the actual delay in the execution of the activity results in the additional, adverse weather induced cost. The cost deals with the constant expenditure related to the utilized renewable resources. The induced cost for the execution mode (i, j) is denoted by $\Delta\tau_{ij}$ and correspond with a whole working shift. The values for all available execution modes are given in the matrix $\Delta\boldsymbol{\tau}$. The matrix is size-compatible with other data matrices: $\mathbf{x}$, $\boldsymbol{\tau}$, $\boldsymbol{\kappa}$.

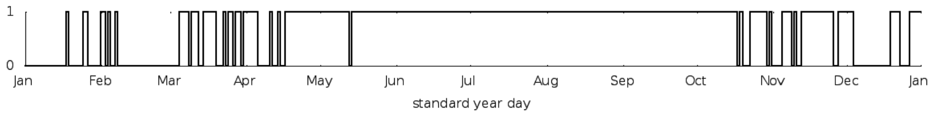


Fig. 2. The standard climatic year-long profile for the sample function $\Omega(i, j, k)$

The computational model is proposed to identify a near Pareto-efficient schedule, while including the influence of poor weather. The appropriate project structure G^*, the corresponding starting date θ_0^*, and allocation of execution modes to activities $\mathbf{x}^*$ are applied in this regard. The model is given in Eqns. (1–6):

$$\min_{G\in\bar{G}}\left\{\min_{\theta_0\in\bar{\theta}}\left\{\min_{\mathbf{x}} F = w_1\frac{T_n(G,\mathbf{x},\boldsymbol{\tau},\mathbf{\Omega},\theta_0)-\theta_0}{\bar{T}} + w_2\frac{C\left(G,\mathbf{x},\boldsymbol{\kappa},\mathbf{\Omega},\Delta\boldsymbol{\kappa},\theta_0\right)}{\bar{C}}\right\}\right\}, \tag{1}$$

$$\underset{i\in\{1,\dots m\}}{\forall} \quad \sum_{j=1}^{o_i} x_{ij} = 1, \quad \underset{i\in\{1,\dots m\}}{\forall} \ \underset{j\in\{1,\dots o_i\}}{\forall} \quad x_{ij}\in\{0,1\}, \tag{2}$$

$$T_0 = \theta_0, \tag{3}$$

$$\underset{k\in\{1,2\dots n\}}{\forall} \ \underset{i\in\Gamma_k^-}{\forall} \ T_k\left(G,\mathbf{x},\boldsymbol{\tau},\mathbf{\Omega},\theta_0\right) \ge t_i^{(s)}\left(G,\mathbf{x},\boldsymbol{\tau},\mathbf{\Omega},\theta_0\right) + \sum_{j=1}^{o_i} x_{ij}\left\{\tau_{ij} + \Delta\tau_{ij}\left[\bar{\theta}(\theta),\mathbf{\Omega}\right]\right\}, \tag{4}$$

$$\underset{k\in\{1,2\dots n\}}{\forall} \ T_k \ge T_{k-1}, \tag{5}$$

$$\underset{k\in\Xi(G)}{\forall} \quad \sum_{(i,j)\in\zeta^{(k)}} x_{ij} \le L_{l(k)}. \tag{6}$$

The goal function that is given in Eqn. (1) deals with the concurrent minimization of project makespan T and total cost C. Note, that the makespan is actually expressed by the difference between the terminal project event occurrence time T_n and the assumed starting date θ_0. The time of the terminal project event occurrence depends on the assumed project structure, the selection of execution modes, the regular activity duration for the execution modes, the general functions of the sensitivity to adverse weather, and the assumed starting date. The total cost of the project also depends on the same entities as well as regular additional cost induced by the delays in the execution of the activities. Project makespan and total cost are brought to the state of the commensurability by the means of the division by the reference values $\bar{T}$ and $\bar{C}$, respectively. Normalized weight values w_1 and w_2 express the relative influence of T and C, respectively.

Note, that the goal function consists of 3 levels. The top level is devoted to the identification of the appropriate project structure G^*, the intermediate level deals with the estimation of the appropriate starting date θ_0^* that corresponds with G^*, and the bottommost level pertains to the appropriate selection of the execution modes $\mathbf{x}^*$.

Eqn.(2) enforces application of a single execution mode only for each activity. Eqn. (3) deals with the definition of the starting project event date.

Formula (4) allows for determining the occurrence dates of consecutive project events T_1, T_2 ...T_n. Symbol Γ_k^- denotes set of activities that finish at the k-th project event, where: $k = 1, 2\ldots n$, and $t_i^{(s)}$ is the time of the occurrence of the starting event for the activity o(i). Note, that both T_k and $t_i^{(s)}$ depend on the assumed project structure, the selected execution modes, the regular duration for the execution modes, the general functions of sensitivity to adverse weather, and the assumed starting date. The second component of the right side of inequality presented in Eqn. (4) expresses the total duration of the activity o(i). Both the regular duration and the induced delays are considered in this regard. The actual delay in the activity o(i) execution is denoted by $\Delta\tau_{ij}$. It depends on the general functions of the sensitivity to adverse weather and the function that maps actual date $\bar{\theta}$ (where: $\bar{\theta} = \theta_0, \theta_1 ... T_n$) onto the corresponding standard climatic year's day θ.

Eqn. (5) assures that the project events occur in the assumed order, while Eqn. (6) deals with the competition between different activities for limited resources.

Let us observe, that the model given in Eqns. (1–6) seems to be mixed linear programming model but it is non-linear, in fact. The non-linearity of the model results from the influence of adverse weather.

3. The applied solution approach

The considered problem is a combinatorial problem because of the numerous feasible project structures and multiple execution modes available for the activities. The non-linearity of the considered problem makes it even more difficult to solve. The parametric decomposition of the original problem is proposed, therefore, to make it easier to solve. The multi level nature of the goal function given in Eqn. (1) is utilized in this regard. The original problem is divided into 3 levels:

1. The upper level deals with the identification of the project structure G^*;
2. The intermediate level is devoted to the estimation of the starting date θ_0^*;
3. The lower level pertains to the selection of the execution modes $\mathbf{x}^*$.
4. Note, that the lower level deals with the tasks that correspond with the representative feasible project structures G, selected out of the set of all feasible project structures $\bar{G}$, and the starting project dates $\theta_0 = 1, 2\ldots365$. The tasks are based on the goal function:

$$\min_{\mathbf{x}} F = w_1 \frac{T_n(G, \mathbf{x}, \boldsymbol{\tau}, \boldsymbol{\Omega}, \theta_0) - \theta_0}{\bar{T}} + w_2 \frac{C(G, \mathbf{x}, \boldsymbol{\kappa}, \boldsymbol{\Omega}, \Delta\boldsymbol{\kappa}, \theta_0)}{\bar{C}}, \tag{7}$$

and the constraints presented in Eqns. (2–6). A locally Pareto-efficient schedule, is therefore obtained for each lower level task [10]. The solutions for the intermediate level tasks and upper level task are provided by the ranking of locally Pareto-efficient schedules, obtained for lower level tasks. Decreasing order of goal function values is applied to create the ranking. Let us also note that, the upper level solution provides a near Pareto-efficient schedule, which is identical with the solution of the original problem.

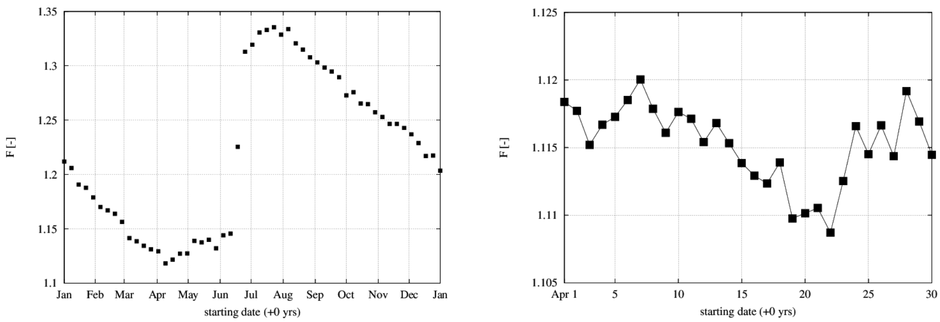
The combinatorial and non-linear nature of the considered problem result in the selection of the Monte Carlo-based approach to solve it. Therefore, the MC-MC approach [10, 12] is applied in this regard.

4. Sample analysis

A sample construction project is applied. The project deals with the erection of the public facility [11]. The project consist of 10 activities. Thirty one different TMSs provide the necessary means for the execution of the activities. The following parameter values are applied in the goal function given in Eqn. (1): $w_1 = 0.3$, $w_2 = 0.7$, $\overline{T} = 354$ days and $\overline{C} = 14,620,000$ PLN. The precedence structure for the project is presented in Fig. 1.

The results obtained for the introductory simulation experiment involving the random generation of 20 project structures and 20 execution mode allocations for each structure, and the 53 starting dates are presented in Fig. 3. The calculations took 9 minutes and 13 seconds of mediocre CPU time. The results reveal that the best starting dates are in April. Analysis of the estimated accuracy and effort [12] suggests the generation of at least 250 project structures and 150 execution mode allocations **x** while searching for the near Pareto-efficient schedules and assuming the 1% overall accuracy level.

Each date in April is utilized as the starting date for the project θ_0 during the final analysis. The analysis results are presented in Fig. 3. The identified near Pareto-efficient schedule corresponds with the starting date of April, the 22nd and the terminal date of the September, the 12th in the following year. The schedule results in the project implementation that lasts for 509 days and costs 14,147,000 PLN. The goal function value is: $F^* = 1.109$. The corresponding project structure is presented in Fig. 2. The calculations took 15 hours 40 minutes and 26 seconds.



The introductory results   The final results

Fig. 3. The obtained results

5. Conclusions

The results presented prove the efficiency of the approach presented, which is capable of providing a near Pareto-efficient schedule for a construction project in a reasonable time. Application of Monte Carlo simulations makes this approach suitable for the analysis of construction projects which consist of different numbers of activities. The most important advantages deal with simplicity, the capability of controlling the actual accuracy of the computations, and a possibility of conducting the multi-level analysis devoted to the step-wise approximation of the most advantageous near Pareto-efficient schedule. The approach is thus worth further development in the future.

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