A FEEDBACK-AWARE VALUATION OF CONSTRUCTION PROJECT EXECUTION TIME

Mirosław Dytczak*
Faculty of Civil Engineering and Environmental Engineering
Białystok University of Technology
Białystok, Poland
E-mail: mdytczak@gmail.com

Grzegorz Ginda
Faculty of Materials and Environment Sciences
University of Bielsko-Biała
E-mail: gg.ginda@gmail.com

Barbara Jastrząbek
Faculty of Materials and Environment Sciences
University of Bielsko-Biała
E-mail: jb-czabak@wp.pl

Tomasz Wojtkiewicz
WACETOB Ltd.
Warsaw, Poland
E-mail: ctb@wacetob.com

ABSTRACT

A makespan and a total cost are universal criteria applied for evaluation of a construction project schedule. These criteria are usually applied simultaneously. Construction projects differ a lot. Hence, weights expressing importance of evaluation criteria should be adjusted to satisfy actual needs. Execution of a construction project takes place in a multi-dimensional surrounding environment consisting of interrelated components. Hence, influence of this environment should be included while deriving values for criteria weights. ANP seems ideal choice in this regard. Reliable application of ANP requires, however, application of an appropriate influence network. We apply DEMATEL to identify influence structure for factors affecting importance of construction project schedule evaluation criteria.

Keywords: construction, project, schedule, criteria, evaluation

1. Introduction

Construction projects consist of time consuming and costly building works. Building works should be executed in an order satisfying technological requirements. There are usually thousands of such feasible orders available. Building works can be also executed using different technology. Application of specific manpower, building materials and equipment as well as financial resources is required in this regard. Such resources are usually available in a limited amount. Actual effects of a construction project execution depend on influence of a surrounding multi-dimensional – economic, social and natural

* Corresponding author

environment. Hence, the identification of an appropriate construction project schedule becomes a difficult and tedious optimisation task.

Two criteria are usually applied to evaluate alternative construction project schedules, namely a construction project makespan and a total execution cost. Simultaneous application of these criteria requires appropriate balancing their influence according to actual conditions in a surrounding environment. Identification of such balance provides us with possibility of making a construction project makespan and a total execution cost commensurable. This allows us to express project execution time in terms of cost and cost in terms of time. Such possibility seems useful while optimizing a construction project schedule – especially in the case of including suspension and delays in executing building works. It can also prove useful in the case of evaluating feasibility of offers made by potential contractors.

We propose, therefore, an approach for a construction project execution time valuation. Both estimated influence of considered construction schedule evaluation criteria and results of bi-criteria construction project schedule optimisation are applied in this regard. We include interactions between surrounding environment components. ANP (Saaty, 1996) is applied, therefore, to derive weight values for construction project schedule evaluation criteria. We must be aware of a fact, however, that obtaining reliable values requires application of adequate ANP network. Hence, it seems that application of appropriate tools for supporting decisions in this regard is indispensable.

There are different suitable tools allowing identification of an appropriate ANP network structure justification. DEMATEL is undoubtedly one of them. Its usability has been recognized only recently, however. For example, Yang et al. (2009) applied DEMATEL for addressing differences in influence relations between different object clusters in ANP models. This concept proved very useful and is called DEMATEL-based ANP (DANP) (Chiu et al., 2013). A straightforward application of DEMATEL is also recommended for identification of appropriate ANP influence network structures (Herat et al., 2012).

It seems, however, that most decision makers aren't in general aware of benefits delivered by coupling DEMATEL and ANP. Hence, we would like to utilise ISAHP forum as means for popularising this approach. We therefore introduce a sample analysis to show both application rules for combining DEMATEL with ANP and resulting benefits.

2. DEcision MAking Trial and Evaluation Laboratory

DEMATEL emerged in the early 70s in last century as a tool for identification of cause-effect chain components. In fact, it was originally developed for identification of true origins of contemporary world problems (Fontela & Gabus, 1974).

DEMATEL applies a concept of direct influence to address relations between decision making problem model components. A structure is expressed by a digraph of direct influence. Digraph vertices correspond to decision making problem model components while digraph arcs indicate direction and strength of direct relations between components.

An ordinal 0-N scale is applied for evaluation of a direct influence. Pair-wise comparisons of decision making problem components are applied in this regard. A scale can consist of different number of levels. Consecutive scale levels denote increasing intensity of a direct influence e.g.:

- 0 – a lack of direct influence of the first compared model component on the second one,
- 1 – a slight influence of the first compared object,
- 2 – a considerable influence of the first compared object,
- 3 – an extreme influence of the first compared object.

A direct influence structure can be expressed by means of a matrix of direct influence **X**. The matrix is quadratic and contains *n* rows and columns pertaining to consecutive decision making problem model components. A matrix element x_{ij} denotes intensity influence of the i-th consecutive model component on the j-th subsequent model component (i,j = 1, 2…n). A direct influence of a model component on itself isn't considered at all and therefore:

$$\underset{i,j=1\ldots n}{\forall} \quad x_{ii} = 0. \tag{1}$$

X provides basis for deriving total influence structure. Total influence includes indirect influence resulting from transmission of direct influence between decision making problem model components. A total influence structure is represented by a matrix of total influence **T**:

$$\mathbf{X} = \overline{\mathbf{X}}\left(\mathbf{I} - \overline{\mathbf{X}}\right)^{-1}, \tag{2}$$

where: **I** denotes an identity matrix and $\overline{\mathbf{X}}$ is a normalized direct influence matrix:

$$\overline{\mathbf{X}} = \frac{\mathbf{X}}{\lambda}, \tag{3}$$

where: λ is a scaling parameter – we receive its value using maximum matrix row-wise and sums column-wise sums:

$$\lambda = \max_{i=1\ldots n}\left\{\sum_{j=1}^{n} x_{ij}, \sum_{j=1}^{n} x_{ji}\right\}. \tag{4}$$

A digraph of total influence is usually applied for representing total a influence structure. It is worth mentioning that DEMATEL is also ready for including opinions of a group of experts.

3. Project execution time valuation

3.1 Identification of an appropriate ANP structure

We take into account influence of factors belonging to 4 distinct dimensions of surrounding environment while evaluating weights for construction project schedule evaluation criteria. The following dimensions are considered:

1. Economic dimension (E).
2. Technical dimension (T).
3. Social dimension (S).
4. Natural environment dimension (N).

The remaining two factors correspond to a construction project makespan (MS) and a total execution cost (EC). All considered dimensions and factors comprise components of a considered decision problem model dealing with estimation of weight values for MS and EC.

Presented approach applies DEMATEL for setting a total influence structure. Opinions of an investor are utilised in this regard. The previously presented 0-3 ordinal scale is applied to assess direct influence of considered decision making problem model components on other components.

The investor assumes that:

1. An economic dimension E slightly influences technical dimension T (evaluation equal to 1). It also influences a social dimension S, a natural environment dimension N and a construction project makespan MS a lot (evaluations equal to 2). A construction project execution cost EC is extremely influenced by an economic dimension (evaluation equal to 3).
2. A technical dimension T slightly influences economic dimension (evaluation equal to 1). It also influences a natural environment dimension a lot (evaluation equal to 2). A construction project makespan and a total execution cost are extremely influenced by a technical dimension (evaluations equal to 3).
3. A social dimension S slightly influences a technical dimension, an economic dimension, a natural environment dimension and a construction project makespan (evaluations equal to 1). A total execution cost is influenced by a social dimension a lot (evaluation 2).
4. A natural environment dimension influences economic dimension, a construction project makespan and a total execution cost a lot (evaluations equal to 2). A technical dimension and a social dimension are slightly influenced by a natural environment dimension (evaluations equal to 1).
5. A construction project makespan slightly influences economic dimension, technical dimension, social dimension and natural environment dimension (evaluations equal to 1). A construction project execution cost is influenced by a construction project makespan a lot (evaluation equal to 2).
6. A total execution cost influences an economic dimension and a construction project makespan a lot (evaluations equal to 2). A social dimension is slightly influenced by a total execution cost (evaluation 1).

A structure of direct influence corresponding to investor's opinions is presented in Fig.1. Applied DEMATEL scale levels are expressed by different line patterns:

- A dotted line denotes a slight direct influence (evaluation equal to 1).
- A solid line corresponds to a big direct influence (evaluation 2).
- A bold line denotes an extreme direct influence (evaluation 3).

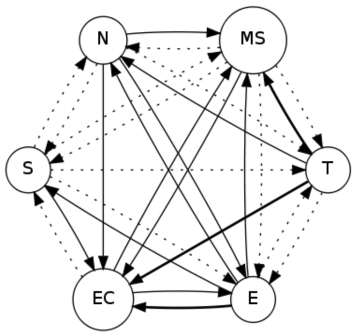

Fig.1 An assumed direct influence structure

We obtain the following matrix of direct influence:

$$\mathbf{X} = \begin{bmatrix} 0 & 1 & 2 & 2 & 2 & 3 \\ 1 & 0 & 0 & 2 & 3 & 3 \\ 1 & 1 & 0 & 1 & 1 & 2 \\ 2 & 1 & 1 & 0 & 2 & 2 \\ 1 & 1 & 1 & 1 & 0 & 2 \\ 2 & 0 & 1 & 0 & 2 & 0 \end{bmatrix}. \quad (5)$$

The largest row-wise and column-wise sum of matrix components is equal to $\lambda = 12$. Hence, we obtain the following normalized matrix of direct influence:

$$\overline{\mathbf{X}} = \begin{bmatrix} 0 & \frac{1}{12} & \frac{1}{6} & \frac{1}{6} & \frac{1}{6} & \frac{1}{4} \\ \frac{1}{12} & 0 & 0 & \frac{1}{6} & \frac{1}{4} & \frac{1}{4} \\ \frac{1}{12} & \frac{1}{12} & 0 & \frac{1}{12} & \frac{1}{12} & \frac{1}{6} \\ \frac{1}{6} & \frac{1}{12} & \frac{1}{12} & 0 & \frac{1}{6} & \frac{1}{6} \\ \frac{1}{12} & \frac{1}{12} & \frac{1}{12} & \frac{1}{12} & 0 & \frac{1}{6} \\ \frac{1}{6} & 0 & \frac{1}{12} & 0 & \frac{1}{6} & 0 \end{bmatrix}. \tag{6}$$

Application of Formula (2) results in the following matrix of total influence:

$$\mathbf{T} = \begin{bmatrix} 0.2089 & 0.1841 & 0.3026 & 0.2913 & 0.4071 & 0.5151 \\ 0.2697 & 0.0961 & 0.1471 & 0.2781 & 0.4590 & 0.4888 \\ 0.2095 & 0.1438 & 0.0982 & 0.1710 & 0.2478 & 0.3412 \\ 0.3186 & 0.1691 & 0.2119 & 0.1297 & 0.3691 & 0.4070 \\ 0.2095 & 0.1438 & 0.1751 & 0.1710 & 0.1708 & 0.3412 \\ 0.2538 & 0.0666 & 0.1711 & 0.0913 & 0.2863 & 0.1711 \end{bmatrix}. \tag{7}$$

A resulting structure of a total influence is presented in Fig.2. Applied line patterns correspond to the following intervals of a total influence:

- dotted line: [0,0.15).
- dashed line: [0.15,0.30).
- solid line: [0.30,0.45).
- bold line: [0.45,+∞).

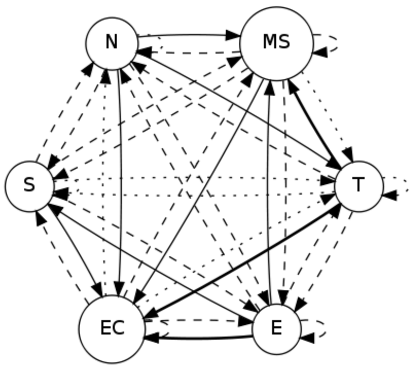

Fig.2 A resulting total influence structure

It is worth noticing that there appears feedback in the case of each distinct decision problem model component. Such feedback results from a transmission of a direct influence through sequences of influenced model components.

3.2 ANP analysis

Obtained total influence structure defines necessary pair-wise comparisons between surrounding environment dimensions and considered construction project schedule evaluation criteria. It proves, therefore, that we should include all model components while considering influence of each distinct component. We use investor's opinions in this regard again.

At first, we deal with influence of an economic surrounding environment dimension E on relations between influence of decision making problem model components on analysis goal. Investor thinks that:

1. An influence of an economic dimension E on analysis goal is the same as influence of a technical dimension T (ANP evaluation equal to 1); the same as, or even slightly larger than, an influence of a social and a natural environment dimension (evaluations equal to 2); slightly larger than an influence of a construction project makespan (evaluation equal to 3) and slightly, or even considerably larger than, an influence of a total construction project execution cost (evaluation equal to 4).
2. An influence of a technical dimension T on analysis goal is slightly larger than an influence of a social and a natural environment dimension (evaluations equal to 3); slightly, or even considerably larger than, an influence of a project makespan (evaluation equal to 4) and considerably larger than an influence of a total execution cost (evaluation equal to 5).
3. An influence of a social dimension is the same as, or even slightly larger than, an influence of a natural environment dimension and a construction project makespan (evaluations equal to 2) and slightly larger than an influence of a total execution cost (evaluation equal to 3).
4. An Influence of a natural dimension is the same as, or even slightly larger than, an influence of a construction project makespan (evaluation equal to 2) and slightly larger than an influence of a total execution cost (evaluation equal to 3).
5. An influence of a construction project makespan is the same as, or even slightly larger than, an influence of a total execution cost (evaluation equal to 2).

A consistent judgement matrix $\mathbf{A}^{(E)}$ (*c.r.* = 0.025) and a resulting priority vector $\mathbf{p}^{(E)}$ look, therefore, as follows:

$$\mathbf{A}^{(E)} = \begin{bmatrix} 1 & 1 & 2 & 2 & 3 & 4 \\ 1 & 1 & 3 & 3 & 4 & 5 \\ \frac{1}{2} & \frac{1}{3} & 1 & 2 & 2 & 3 \\ \frac{1}{2} & \frac{1}{3} & \frac{1}{2} & 1 & 2 & 3 \\ \frac{1}{3} & \frac{1}{4} & \frac{1}{2} & \frac{1}{2} & 1 & 2 \\ \frac{1}{4} & \frac{1}{5} & \frac{1}{3} & \frac{1}{3} & \frac{1}{2} & 1 \end{bmatrix} \Rightarrow \mathbf{p}^{(E)} = \begin{bmatrix} 0.2602 \\ 0.3244 \\ 0.1560 \\ 0.1258 \\ 0.0815 \\ 0.0521 \end{bmatrix}. \qquad (8)$$

Obtained partial results make it evident that a technical dimension and an economic dimension affect analysis goal at most while considering influence of an economic dimension. The remaining surrounding environment dimensions affect analysis goal moderately. Both construction project schedule evaluation criteria influence analysis goal rather slightly. An influence of a construction project makespan is noticeably larger, however, than an influence of a total execution cost.

Investor's opinions corresponding to influence of a technical surrounding environment dimension T result in a consistent judgement matrix $\mathbf{A}^{(T)}$ (*c.r.* = 0.036) and a resulting priority vector $\mathbf{p}^{(T)}$:

$$\mathbf{A}^{(\mathrm{T})}=\begin{bmatrix}1 & \frac{1}{3} & \frac{1}{2} & 1 & 3 & 4\\ 3 & 1 & 2 & 3 & 4 & 5\\ 2 & \frac{1}{2} & 1 & 3 & 4 & 4\\ 1 & \frac{1}{3} & \frac{1}{3} & 1 & 3 & 3\\ \frac{1}{3} & \frac{1}{4} & \frac{1}{4} & \frac{1}{3} & 1 & 1\\ \frac{1}{4} & \frac{1}{5} & \frac{1}{4} & \frac{1}{3} & 1 & 1\end{bmatrix} \quad\Rightarrow\quad \mathbf{p}^{(\mathrm{T})}=\begin{bmatrix}0.1450\\0.3522\\0.2507\\0.1343\\0.0589\\0.0539\end{bmatrix}. \tag{9}$$

A technical dimension proves to be the most influencing component again. A social dimension is the second most influencing component. The remaining surrounding environment dimensions affect analysis goal rather moderately. Influence of both a construction project makespan and a total execution cost is small.

A judgement matrix $\mathbf{A}^{(S)}$ and a priority vector $\mathbf{p}^{(S)}$ obtained for social surrounding environment dimension S influence look as follows:

$$\mathbf{A}^{(\mathrm{S})}=\begin{bmatrix}1 & \frac{1}{2} & \frac{1}{3} & \frac{1}{2} & 2 & 3\\ 2 & 1 & \frac{1}{2} & 1 & 2 & 3\\ 3 & 2 & 1 & 2 & 3 & 4\\ 2 & 1 & \frac{1}{2} & 1 & 2 & 3\\ \frac{1}{2} & \frac{1}{2} & \frac{1}{3} & \frac{1}{2} & 1 & 2\\ \frac{1}{3} & \frac{1}{3} & \frac{1}{4} & \frac{1}{3} & \frac{1}{2} & 1\end{bmatrix} \quad\Rightarrow\quad \mathbf{p}^{(\mathrm{S})}=\begin{bmatrix}0.1322\\0.1918\\0.3280\\0.1918\\0.0964\\0.0598\end{bmatrix}. \tag{10}$$

A social dimension proves the most influencing model component. Other surrounding environment dimensions seem to influence analysis goal rather moderately. A construction project schedule evaluation criteria are the least influencing model components. An influence of a construction project makespan is noticeably larger, however, than influence of a total execution cost.

We obtain the following judgement matrix $\mathbf{A}^{(N)}$ and a corresponding priority vector $\mathbf{p}^{(N)}$ while considering a natural surrounding environment dimension N influence:

$$\mathbf{A}^{(\mathrm{N})}=\begin{bmatrix}1 & \frac{1}{3} & \frac{1}{2} & \frac{1}{3} & 2 & 2\\ 3 & 1 & \frac{1}{2} & 1 & 2 & 3\\ 2 & 2 & 1 & \frac{1}{2} & 3 & 3\\ 3 & 1 & 2 & 1 & 3 & 3\\ \frac{1}{2} & \frac{1}{2} & \frac{1}{3} & \frac{1}{3} & 1 & 1\\ \frac{1}{2} & \frac{1}{3} & \frac{1}{3} & \frac{1}{3} & 1 & 1\end{bmatrix} \quad\Rightarrow\quad \mathbf{p}^{(\mathrm{N})}=\begin{bmatrix}0.1146\\0.2140\\0.2375\\0.2814\\0.0789\\0.0736\end{bmatrix}. \tag{11}$$

A natural environment dimension proves to be the most influencing component. A technical dimension and a social dimension seem to affect analysis goal considerably, too. An influence of an economic dimension seems to be rather average. Both construction project schedule evaluation criteria affect analysis goal only slightly.

A judgment matrix $\mathbf{A}^{(MS)}$ and a priority vector $\mathbf{p}^{(MS)}$ resulting from comparison of model components according to influence of a construction project makespan are presented in Equation (12):

$$\mathbf{A}^{(MS)} = \begin{bmatrix} 1 & \frac{1}{2} & 1 & \frac{1}{2} & \frac{1}{2} & 3 \\ 2 & 1 & 2 & 1 & 1 & 3 \\ 1 & \frac{1}{2} & 1 & 1 & 1 & 3 \\ 2 & 1 & 1 & 1 & 1 & 3 \\ 2 & 1 & 1 & 1 & 1 & 3 \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3} & \frac{1}{3} & \frac{1}{3} & 1 \end{bmatrix} \Rightarrow \mathbf{p}^{(MS)} = \begin{bmatrix} 0.1313 \\ 0.2313 \\ 0.1657 \\ 0.2050 \\ 0.2050 \\ 0.0617 \end{bmatrix}. \quad (12)$$

It proves that a technical surrounding environment dimension, a natural environment dimension and a construction project makespan influence analysis goal at most. An influence of a social dimension and an economic dimension is moderate. A total execution cost proves the least influencing model component again.

We finally obtain a judgment matrix $\mathbf{A}^{(CE)}$ and a priority vector $\mathbf{p}^{(CE)}$ resulting from considering an influence of a total execution cost:

$$\mathbf{A}^{(CE)} = \begin{bmatrix} 1 & \frac{1}{3} & \frac{1}{2} & \frac{1}{3} & 2 & \frac{1}{2} \\ 2 & 1 & 2 & 2 & 3 & 2 \\ 1 & \frac{1}{2} & 1 & \frac{1}{2} & 2 & 1 \\ 2 & 1 & 1 & 1 & 3 & 2 \\ 2 & 1 & 1 & 1 & 1 & \frac{1}{2} \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3} & \frac{1}{3} & \frac{1}{3} & 1 \end{bmatrix} \Rightarrow \mathbf{p}^{(CE)} = \begin{bmatrix} 0.0934 \\ 0.3013 \\ 0.1464 \\ 0.2392 \\ 0.0733 \\ 0.1464 \end{bmatrix}. \quad (13)$$

A technical surrounding environment dimension influences analysis goal at most. An influence of a natural environment dimension is also considerable. A social dimension and a total execution cost influence analysis goal moderately. Influence of the remaining model components is rather insignificant.

Priority vectors obtained while considering influence of different model components make building the following ANP supermatrix possible:

$$\mathbf{S} = \left[\mathbf{p}^{(E)} \quad \mathbf{p}^{(T)} \quad \mathbf{p}^{(S)} \quad \mathbf{p}^{(N)} \quad \mathbf{p}^{(MS)} \quad \mathbf{p}^{(CE)} \right] \quad . \quad (14)$$

Application of the supermatrix results in a limit supermatrix giving final priorities **P** presented in Equation (15). They are obtained just after 15 consecutive supermatrix multiplications.

$$\mathbf{P} = \left[0.1503 \quad 0.2699 \quad 0.2380 \quad 0.1874 \quad 0.0889 \quad 0.0655 \right]^{T} \quad . \quad (15)$$

A technical dimension T and a social dimension S prove the most influencing model components. The remaining surrounding environment dimensions seem to influence evaluation of construction project schedule criteria moderately. Priorities obtained for criteria allow to assess their relative share in a construction project schedule evaluation . It proves that a share of a construction project makespan is equal to w_1 = 0,5760 while a share of a total execution cost is equal to w_2 = 0,4240.

3.3 Estimation of a construction project execution time value

We apply Pareto-efficient results of a bi-criteria, makespan-total execution cost construction project schedule optimisation to include the most beneficial properties of construction project schedules. Derived information about relative share of both evaluation criteria is utilised in this regard. A following function is applied, therefore, to evaluate a construction schedule:

$$f = w_1 \cdot \frac{T - T_{\min}}{T_{\max} - T_{\min}} + w_2 \cdot \frac{C - C_{\min}}{C_{\max} - C_{\min}}, \tag{16}$$

where: T denotes a construction project makespan and $T_{\min}$, $T_{\max}$ are the minimal and the maximal construction makespan, respectively, corresponding to Pareto-efficient optimisation results; C is a total execution cost and $C_{\min}$, $C_{\max}$ are the minimal and the maximal total execution cost, respectively, corresponding to Pareto-efficient optimisation results.

We assume that final value of a construction project execution time c_T corresponds to optimal value $f_{\min}$ of the goal function presented in Equation (16):

$$c_T = \frac{C(f_{\min})}{T(f_{\min})}, \tag{17}$$

where: $C(f_{\min})$, $T(f_{\min})$ denote a total construction project execution cost and a construction project makespan, respectively, corresponding to optimal value of function f.

We apply a sample construction project to illustrate proposed approach for construction project execution time valuation. Pareto-efficient results of project optimisation for a sample construction project are presented in Table 1 together with corresponding f function values.

Table 1. Pareto-efficient results of a sample project optimisation

No.	T [h]	C [PLN]	f [-]
1	1832	13,718,000	0.4240
2	**1840**	**13,690,000**	**0.4211**
3	1856	13,672,000	0.4328
4	1882	13,650,000	0.4554
5	1890	13,622,000	0.4525
6	1932	13,538,000	0.4664
7	1940	13,510,000	0.4635
8	1956	13,492,000	0.4753
9	1982	13,470,000	0.4978
10	1990	13,442,000	0.4949
11	2032	13,198,000	0.4348
12	2040	13,170,000	0.4319
13	2056	13,152,000	0.4437
14	2082	13,130,000	0.4662
15	2090	13,102,000	0.4633
16	2140	13,082,000	0.5169
17	2232	12,898,000	0.5474
18	2240	12,870,000	0.5445
19	2256	12,852,000	0.5563
20	2282	12,830,000	0.5789
21	2290	12,802,000	0.5760

Optimal value for f is obtained for a makespan equal to 1840 h and a total execution cost equal to 13,690,000 PLN. Hence, we obtain c_T = 7440 PLN/h according to Formula (17).

4. Conclusions

Valuation of construction project execution time delivers important information for optimising and evaluating construction project schedules. Information about time value makes it also possible to evaluate feasibility and reliability of offers of potential contractors while searching for the most beneficial offer during a tender procedure execution. Hence, this information helps in gaining benefits and avoiding a possible considerable loss in time, money or productivity successfully while dealing with costly and time-consuming construction projects.

Presented time valuation approach enables us to derive and utilise information about relative influence of considered criteria for evaluation of construction project schedule. ANP application makes the presented approach capable of including complex and interrelated influence of a surrounding environment on effects of a construction project execution while deriving relative influence of considered construction project schedule evaluation criteria. It also applies Pareto-efficient results of construction project schedule optimisation to include the most beneficial properties of a construction project schedule.

We are sure that the presented approach lacks some usable features. We intend, therefore, to develop it further. For example, we want to include opinions of multiple stakeholders to include possible diversity in points of view and to allow including stochastic nature of surrounding environment.

We must be also aware of a successful ANP application dependence on proper influence network structure choice. Results of presented sample analysis show that merits of DEMATEL make it an attractive tool for deriving a proper influence structure for ANP. Additional DEMATEL benefits for ANP users result from similarity of applied ordinal evaluation scale, application of a pair-wise comparisons while evaluating a direct influence between decision making problem model components and application of an ANP-compatible digraph representation of an influence structure.

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