Methodology for Developing Probabilistic Productivity Norms in Civil Engineering

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Successful implementation of the Critical Path Method requires availability of clearly defined duration for each activity, while the PERT method is based on personal estimation. However, due to the long duration of the construction and unpredicted delays that accompany this process, it is often difficult or almost impossible to predict exact duration of an activity, and consequently to take it for granted that the given activity will be finished on the very same day that is given in the dynamic plan of construction. The aim of presented research was to establish methodology for developing new productivity norms for construction works for planning under uncertainty.

Key words: productivity norms, dynamic plans, uncertainty

1. INTRODUCTION

In construction industry, productivity norm can be defined as time required by a skilled worker qualified for a given type of work to successfully complete specific procedure and/or sequence of work operations with satisfactory quality using appropriate tools and/or machines, in average surrounding and ambient conditions, with normal effort and fatigue.

Standard productivity norms, which have been used for decades in civil engineering for calculating and planning duration of the construction works, can be basically described as deterministic, because they are always precisely and strictly defined by an exact number. However, in realistic situations in practice, there are many cases where an activity duration cannot be presented in a precise manner, especially in construction projects.

Durations of different activities are usually taken from the productivity norms for man-hours calculation [1], which are often too generalized and sometimes

obviously not accurate. For example, productivity rates for man-hours calculation for in-situ reinforcement fixing are based only on total amount of the reinforcing steel, regardless of the pattern complexity which can greatly affect time needed for proper placing, tying and control. Because of that, patterns consisting of 12Ø16 and 3Ø32 bars, respectively, have exactly the same total amount of steel and consequently the same theoretical number of man-hours needed for placing and fixing, although it is obvious that such result would not be realistic, as was proven in studies [2, 3].

Besides that, Proverbs et al. [4] have proven that productivity rates can significantly vary from country to country. All these factors can lead to an unreliable dynamic plan for a given construction project. Critical Path Method (CPM), known in practice for decades, is characterized by the fact that the duration of any activity in the network diagram is known and expressed deterministically (by one exact number).

However, in the general dynamic plan of construction process, it would be more desirable and realistic to have the duration of any construction activity and deadline for its accomplishment expressed as an interval of a few days rather than one specific day or date [5].

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The first solution of this problem has emerged in the form of the PERT method (Program Evaluation and Review Technique), based on the theory of probability, but the application of this method in practice is very limited due to the fact that existing production norms provide only average times for accomplishing different activities, while the other required data, such as optimistic and pessimistic times, have to be estimated subjectively or by using database with collected data from previous projects and/or experiences.

The aim of presented study was to introduce probabilistic approach in planning by creating productivity norms that provide not only average or most likely time, but also optimistic and pessimistic time for each activity, based not on individual estimation but on realistic data obtained by the field research and illustrated by the example of times needed for laying ceramic floor and wall tiles.

2. PROBABILISTIC APPROACH

Although the CPM technique has become widely recognized as valuable tool for planning and scheduling large construction projects, this method is based on clearly determined time duration for each activity.

However, due to the complexity of construction projects, their long duration and accompanied and unavoidable risks, it is often unrealistic to expect that a given activity, group of activities or the entire project will be accomplished exactly on the day given in the dynamic plan of construction. This results in an unreliable dynamic plan for construction process.

In order to create a realistic and more applicable progress schedule in the construction industry, it is often better to use the PERT method, which does not provide exact date of accomplishing given task, but the time interval in which the task will be accomplished, thus including the element of uncertainty in order to provide expected time-frame for the network chart [6].

In this approach, every activity's duration is described by a set of three data that can be obtained by a statistical study or subjective estimation:

- t_o = optimistic time – minimum possible time required to accomplish the task;
- t_m = most likely time – activity duration with high probability of completing the task;
- t_p = pessimistic time – maximum possible time required to accomplish the task.

These three variables are used for calculating the expected time (t_e), defined as most probable (average) time for accomplishing given activity:

$$t_e = \frac{t_p + 4t_m + t_o}{6} \quad (1)$$

with standard deviation:

$$\sigma_{te} = \frac{t_p - t_o}{6} \quad (2)$$

Although the PERT method has proven to be a reliable source for making dynamic plans, its application in engineering practice is limited by the fact that official productivity norms offer only most likely time, while optimistic and pessimistic time have to be estimated by an individual's estimation based on experience. This paper presents methodology for developing database of norms applicable for the PERT method, in which each activity is described by its three characteristic times, namely: optimistic, most likely and pessimistic time. Further improvement of the method can be achieved by introducing the level of probability of accomplishing given task in order to enable the planner to choose between higher and lower accuracy.

3. DATA COLLECTING AND PROCESSING

Proposed methodology for developing empirical productivity norms that would be applicable in the PERT method (Figure 1) will be illustrated by the example of productivity norms for setting different types of ceramic tiles.

Figure 1 - Algorithm for obtaining probabilistic productivity norms

In order to gather data for developing adequate probabilistic norms, a field research was conducted on five on-going building sites. Research included 24 tile setters. Times needed for laying 12 different types of tiles were measured and expressed as time necessary for laying 1 m² of tiles, i.e. min/m². Examined activities are presented in Table 1. Obtained times for each tile type were grouped into intervals of 2 minutes, where a nominal value for each interval is expressed

by its mean value, and presented graphically as frequency polygon that shows number of results in each interval (Figure 2). Shape of obtained polygons indicates that the most appropriate function approximation in all cases would be the normal (Gaussian) distribution.

Empirical and calculated values for Gaussian distributions are presented in Table 2.

Table 1. Considered types of ceramic tiles

ID	Description	ID	Description
SRW 1	Laying ceramic floor tile 10x20 in cement mortar	SRW 7	Laying ceramic wall tile 15x15 in cement mortar with highlighted joints
SRW 2	Laying ceramic floor tile 10x20 with adhesive	SRW 8	Laying ceramic wall tile 10x20 in cement mortar
SRW 3	Laying ceramic floor tile 10x10 in cement mortar	SRW 9	Laying ceramic wall tile 10x20 in cement mortar with highlighted joints
SRW 4	Laying ceramic floor tile 10x10 with adhesive	SRW 10	Laying ceramic wall tile 15x15 with adhesive
SRW 5	Laying ceramic floor tile 20x20 in cement mortar	SRW 11	Laying ceramic wall tile 15x15 with adhesive with highlighted joints
SRW 6	Laying ceramic wall tile 15x15 in cement mortar	SRW 12	Laying ceramic wall tile 10x20 with adhesive

Table 2. Empirically obtained times and calculated values for Gaussian distributions

ID	μ_E	σ_E	μ_A	σ_A	NP	DF	χ^2	R ²
SRW 1	98.05	5.48	98.00	5.15	9	5	2.640	0.95
SRW 2	78.22	6.05	77.90	3.07	10	6	6.560	0.89
SRW 3	105.80	6.63	105.80	3.66	11	7	1.359	0.98
SRW 4	85.84	6.05	86.15	2.91	10	6	7.300	0.88
SRW 5	90.12	5.48	90.29	3.86	9	5	2.400	0.92
SRW 6	128.14	6.63	128.00	4.10	11	7	3.30	0.94
SRW 7	157.68	6.63	157.60	4.256	11	7	3.82	0.90
SRW 8	161.60	6.053	161.44	5.634	10	6	8.79	0.82
SRW 9	199.01	5.47	199.44	2.91	9	5	4.92	0.93
SRW 10	80.41	5.47	81.20	2.32	9	5	0.78	0.98
SRW 11	101.65	6.05	101.92	3.70	10	6	2.37	0.95
SRW 12	105.69	6.63	105.40	4.39	11	7	14.03	0.80

($\sim_E$ – mean empirical value [min/m²]; $\uparrow_E$ – standard deviation of the empirical data; $\sim_R$ – mean value of approximation; $\uparrow_R$ – standard deviation of the approximation; NP – Number of points; DF – degrees of freedom; χ^2 – chi square; R² – coefficient of determination)

Figure 2 - Frequency polygons and approximations

In order to estimate accuracy of adopted approximations, it is necessary to perform a significance tests that include calculating values of correlation coefficient, coefficient of determination, chi-squared and Fisher's analysis of variance [7]. Results of performed tests are presented in Tables 3.

High values of the correlation coefficient (ranging from 0.894 to 0.989) indicate strong correlation between the empirical data and the Gaussian distribution. Values of the coefficient of determination vary from 0.80 to 0.98, which gives average variation of 0.9 between the empirical and Gaussian distribution, meaning that approximation function passes through approximately 90% points on the scatter plot, so it can

be concluded that the empirical data are well represented by the Gaussian distribution [8].

It can be further observed that all calculated values t^c are lower than critical values t^c_r , which indicates that any discrepancy between the frequencies of the empirical and Gaussian distribution can be considered as a random one.

Only two calculated value of F (SRW4 and SRW10) are equal to or greater than the critical values $F_{, N1-, N2-1}$, which can be considered as random error. All other values meet the criterion $F < F_{, N1-, N2-1}$, so it can be concluded that differences found between the variances have no statistical significance.

Table 3. Significance tests results

ID	R ²	R	χ^2	DF	$\chi^2\alpha$	σ^2_E	σ^2_A	F	$F\alpha, N1-, N2-1$
SRW 1	0.955	0.977	2.640	5	11.10	30.03	26.52	1.132	5.0503
SRW 2	0.890	0.943	6.560	6	12.60	36.60	9.42	3.885	4.2839
SRW 3	0.980	0.989	1.359	7	14.10	43.96	13.39	3.283	3.7870
SRW 4	0.880	0.938	7.300	6	12.60	36.60	8.47	4.321	4.2839
SRW 5	0.920	0.959	2.400	5	11.10	30.03	14.90	2.033	5.0503
SRW 6	0.940	0.969	3.300	7	14.10	43.96	16.81	2.615	3.7870
SRW 7	0.900	0.948	3.820	7	14.10	43.96	21.16	2.077	3.7870
SRW 8	0.820	0.905	8.790	6	12.60	36.60	31.70	1.154	4.2839
SRW 9	0.930	0.964	4.920	5	11.10	29.92	8.47	3.532	5.0503
SRW 10	0.980	0.989	0.781	5	11.10	29.92	5.38	5.561	5.0503
SRW 11	0.950	0.974	2.370	6	12.60	36.60	13.69	2.673	4.2839
SRW 12	0.800	0.894	14.030	7	14.10	43.96	19.27	2.281	3.7870

(R² - coefficient of determination, R - correlation coefficient, t^c - chi-squared value, DF - degrees of freedom, $\chi^2\alpha$ - critical values, σ^2_E - variance from the empirical data, σ^2_A - variance from the approximation values, DF - degrees of freedom, $F_{, N1-, N2-1}$ - critical values)

4. PROBABILISTIC PRODUCTIVITY NORMS

Based on statistical analysis, probabilistic productivity norms have been developed using probability distribution. Two cases were examined - probabilities of 68% and 96%, which are corresponding values for ± 2 and 3 standard deviations around the mean value (Figure 3) [9].

Due to the so-called "three sigma rule", it can be assumed that all probabilities out of 3σ limit (equal or greater than 99.7%) can be considered as "near certainty" [9].

Therefore, optimistic times (t_o) were obtained by adding one, respectively two, standard deviations to the mean time ($t_m = \mu$), and pessimistic times (t_p) are obtained by subtracting these values.

Figure 3 - Probability distribution

Values presented in Table 4 are optimistic, mean and pessimistic times with probability of accomplishing a given task of 68 and 96%, respectively. These values can be successfully implemented in the PERT method or other methods for planning for planning

under uncertainty [10], so it can be talked about within a given time period with probability of 68 or accomplishing the set of activities or entire project 96%.

Table 4. Probabilistic productivity norms for probabilities of 68 and 96 %

ID	Probability 68 %			Probability 96 %		
	$t_o (\mu - \sigma)$	$t_m (\mu)$	$t_p (\mu + \sigma)$	$t_o (\mu - 2\sigma)$	$t_m (\mu)$	$t_p (\mu + 2\sigma)$
SRW 1	92,5	98	103,15	87,35	98	108,3
SRW 2	74,3	77,9	80,97	71,23	77,9	84,04
SRW 3	102,14	105,8	109,46	98,48	105,8	113,12
SRW 4	83,24	86,15	89,06	80,33	86,15	91,97
SRW 5	86,43	90,29	94,15	82,57	90,29	98,01
SRW 6	123,9	128	132,1	119,8	128	136,2
SRW 7	153,34	157,6	161,86	149,08	157,6	166,12
SRW 8	155,81	161,44	167,07	150,18	161,44	172,7
SRW 9	196,49	199,4	202,31	194,39	199,4	205,22
SRW 10	78,88	81,2	83,52	76,56	81,2	85,84
SRW 11	98,22	101,92	104,9	94,52	101,92	108,6
SRW 12	101,01	105,4	109,79	96,62	105,4	123,78

5. CONCLUSION

Productivity norms commonly used for planning and scheduling construction project offer only one deterministic time for accomplishing each given activity. These data are often criticized in practice on the ground that their values are unrealistic and/or unattainable. The main downside of such norms is that they cannot be used for risks planning and scheduling under uncertainty.

This paper presents methodology for developing probabilistic productivity norms based on realistic data obtained at the building sites, providing not only average time for accomplishing a given task, but the time period within which a given activity will be finished with predefined probability of accomplishment. These norms can be successfully applied in probabilistic methods for planning under uncertainty.

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REZIME

METODOLOGIJA IZRADE PROBABILISTIČKIH NORMATIVA U GRAĐEVINARSTVU

Za uspješnu primenu metode kritičnog puta neophodno je znati tačno trajanje svake aktivnosti, dok se PERT metoda zasniva na ličnoj proceni ili ranije prikupljenim podacima. Međutim, zbog dugog trajanja građevinskih projekata i nepredviđenih zastoja, često je teško, pa čak i gotovo nemoguće predvidjeti tačno trajanje svake aktivnosti i smatrati za sigurno da će određena aktivnost biti okončana baš onog dana koji je predviđen dinamičkim planom. Cilj istraživanja prikazanog u ovom radu bio je da se razvije metodologija za izradu novih normativa za građevinske radove koji bi mogli da se koriste za planiranje u uslovima neizvesnosti.

Ključne riječi: *normativ, dinamički planovi, neizvesnost*