Scheduling Repetitive Construction Processes Using the Learning-Forgetting Theory

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Abstract. One of the main factors having a decisive impact on the completion date of a construction project and its total cost is the duration of individual processes. Projects such as the construction of multi-storey residential and public buildings, line facilities, highways, networks of external installations or pipelines are conducted with time-location methods of work organization. It is possible to notice the cyclical nature of building processes in projects, whose characteristic parameter is length or height. In such cases, works are entrusted to specialized organizational units (crews, teams) that conduct repeated operations on identical or similar sections, called units. With each repetition of the operations, workers acquire more and more practical experience which has a positive effect on their work efficiency and leads to a reduction in the time and cost of a construction project. The learning theory bring on a mathematical description of the interdependence between the repetitions number of the same task and work efficiency. Taking into account the learning effect allows for a more accurate estimation of the individual construction processes duration, which may provide an advantage at the stage of submitting bids in tenders. The aim of research is to prepare the implementation plan of repetitive construction processes conducted in a multi-storey residential building. The schedule will take into account the impact of the learning and forgetting effect for the duration of construction works and the interruptions in crews work on the example of finishing works. Due to the lack of commercial software for preparing construction schedules taking into account the learning and forgetting impact, a spreadsheet was developed in MS Excel to set the start and end dates and time buffers of construction processes.

1. Introduction
Plenty of construction projects are composed of processes which are repeated a number of times on identical or similar structures or their sections called construction units. Among the examples of such projects are multi-storey residential and public buildings (mostly multi-sectional), linear objects: highways, exterior installation networks and more. The same kind of processes is conducted by construction crew during the works involving many objects or sections of a similar construction type. The crews carry out the same kind of processes on different units and at the next building sites. For this reason, it is possible to apply the learning theory, describing/explaining the correlation between the acquired experience through realizing similar tasks and the size of the production. In practice, the learning curve is used in performance improvement modelling, which usually stems from experience, not from theoretical acquisition of knowledge. This assumption finds its application while performing single manufacturing operations during which the workers continuously develop their skills or work to improve the efficiency of their position [1]. The increase in the number of repeated operations leads to the acquisition of growing practical experience and thus to a reduction of time, and sometimes cost, of...
the realization. A continuous repetition of the processes leads to a more efficient use of tools as well as it facilitates the coordination and work supervision.

Scheduling repetitive processes takes advantage of the LOB method – Line of Balance – and its extensions: Linear Scheduling Method (LSM) [2], Productivity Scheduling Method (PSM) [3], Vertical Production Method (VPM) [4], Repetitive Scheduling Method (RSM) [5], Horizontal and Vertical Logic Scheduling (HVLS) – [6] and the combination of the CPM and LOB methods [7] further improved by [8]. These techniques make the elimination of CPM and PERT imperfections possible in the course of scheduling repetitive processes. They are based on a graphic model, optimization methods and, above all, on the analysis of relations or connections between the performance of crews in different construction units.

Scheduling works for crews is an elementary problem in construction project planning [9]–[14], and for that reason constitutes a popular subject in studies. The problem of the influence of experience on the duration of repetitive processes has been analyzed in the field of construction multiple times [15]–[17]. It is essential to determine the performance of work in order to prepare a real process realization schedule. In the stage of construction realization planning it is necessary to consider the possibility to reduce the duration of the processes thanks to the experience developed at other building sites. With this approach a company may improve its competitive position while engaging in tender biddings related to construction projects.

Calculation spreadsheets are an efficient tool with a wide scope of calculations applied in a number of fields. The literature has often provided attempts of algorithm implementations in MS Excel for the purpose of automation in construction projects planning models by means of various techniques [18], [19]. Nevertheless, none of these papers consider a possibility of time reduction thanks to the effect of learning nor its prolongation caused by the effect of forgetting.

2. The learning-forgetting theory

The learning theory explains mathematically the relation between the number of repetitions performed in the same work and the resulting performance. The use of the learning theory in the construction industry is limited. This is owing to the changeable conditions of work and the inability to provide the crews with the opportunity of conducting uninterrupted works while performing technologically homogenous processes in the consecutive stages of construction. Due to the discontinuity in the carrying out of the processes, it is necessary to consider the effect of forgetting, which is proportional to the duration of the intervals (periods of time when a brigade does not carry out works of the same kind).

The first learning model was formulated in 1936 by Wright [20]. It assumes the form of an exponential curve of the following equation:

$$t_n = t_1 \cdot n^{-l}, \quad (1)$$

where: $t_n$ – process duration in a unit $n$, $t_1$ – process duration in the first construction unit, $n$ – the number of process repetitions (number of the next unit), $l$ – reduction parameter, which determines the shape of the logarithmic curve.

It was assumed in the model that the reduction parameter may be determined on the basis of the following relation:

$$l = -\frac{\log s}{\log 2}, \quad (2)$$

while the $s$ value is called the learning rate, defined as a percentile of time reduction resulting from doubling the number of the realized production units (1-s value) is called the reduction coefficient.

In the cases when the workers take advantage of their previously acquired experience, for example at other construction sites, it is possible to apply the Stanford-B model [21] in order to describe the learning curve. It is expressed in the following relation:
\[ t_n = t_1 \cdot (n + B)^{-l}, \] (3)

where: \( B \) – equivalent of the previously acquired experience, which constitutes a hypothetical number of previously performed work repetitions.

One of the inconveniences in using an exponential function in a learning model is the fact that in the case of a large number of repetitions the process duration is approaching 0.

In the case of partly or completely mechanized processes, it is a common practice to apply the DeJong’s model, which introduces the \( M \) coefficient related to the degree of the process mechanization. In this model it was assumed that as a result of repetition manually performed processes undergo a more significant reduction in their duration than those which are mechanized. The model proposed by DeJong \[22\] takes the following form:

\[ T_n = T_1 \cdot [M + (1-M) \cdot n^{-l}], \] (4)

where: \( M \) – coefficient of the process automation rate \( M \in [0, 1] \); it assumes the value 0 when the process is performed manually, and \( M=1 \) for the fully automated process. The DeJong model is used in many companies, mostly industrial ones due to its simplicity.

Due to the fact that, as it was confirmed by empirical studies, the Stanford-B model is more precise in describing the effect of learning in the first stages of learning, while the DeJong’s model proves better in the subsequent phases, Carlson \[21\] combined the two approaches in a single model of the following form:

\[ T_n = T_1 \cdot [M + (1-M) \cdot (n + B)^{-l}]. \] (5)

Mazur and Hastie \[23\] proposed a commonly accepted model in which the work performance \( w_n \) changes according to the number of repetitions \( n \):

\[ w_n = k \left( \frac{n + p}{n + p + r} \right), \quad w_n, k, p, n \geq 0, p + r > 0, \] (6)

where: \( k \) – is the maximum performance, \( p \) – previously acquired experience from the similar works performed in the past measured using the same units as \( n \), while \( r \) – is the number of required repetitions which guarantee reaching half of the performance \( k \) assuming that the work is commenced with no previous experience.

Having analyzed the literature on the topic, it needs to be stated that a single universal learning curve does not exist. An approach used to consider the effect of learning ought to enable simple yet precise estimation of model parameters on the basis of a small amount of data derived from the previously realized processes. The assumed model, however, should properly reflect the observed learning phenomenon for the kind of process that is analyzed.

The lack of continuity in the works of crews carrying out repetitive processes leads to increased duration. When the interruptions are short, only a part of the experience is wasted. If the interruption is long enough, the reduction of the time used for the process induced by the learning effect is lost \[24\]. There is a scarce number of works related to the forgetting theory as it is difficult to identify the relation between the length of interruptions, the acquired level of experience and the loss of it. The process of forgetting triggered by the interruptions while carrying out the works is a reversed phenomenon to the process of knowledge acquisition \[25\], \[26\]. It leads to an elongation of the time needed to perform the processes in the units, which may be described using the relation \[27\], \[28\]:

\[ \hat{t}_s = \hat{t}_1 \cdot x^f, \] (7)
where: \( \tilde{t}_i \) – time used to carry out the process in a unit \( x \) as a result of the forgetting effect, \( \hat{t}_i \) – equivalent time used to carry out the process in the first unit in the forgetting process, \( x \) – the number of units which would have been realized during the interval, while \( f \) is the exponent of the forgetting curve.

In his model called VRIF (Variable Regression Invariant Forgetting Model), Elmaghraby [29] assumes that \( f \) is constant and its value can be determined on the basis of the first equivalent performance time \( \hat{t}_i \) in the first learning-forgetting cycle (figure 1). The duration times of the processes at the end of the learning stage and at the beginning of the forgetting stage (the intersection of the learning curve and the forgetting curve in the figure 1) are equal. Therefore, by comparing the expressions (1) and (7) it is possible to determine the time \( \hat{t}_i \):

\[
\hat{t}_i = t_i \cdot q^{-l(l+f)},
\]

while the remembered equivalent number of the realized units (acquired experience) at the beginning of the cycle \( (i+1) \) after the occurrence of an interval \( i \) will equal:

\[
u_{i+1} = \left( \frac{\hat{t}_i}{t_i} \left( q_i + s_i \right)^l \right)^{-\frac{l}{l+f}}, (9)
\]

where: \((q_i + s_i)\) is the number of units which could have been realized before the end of the interval.

Assuming that the total loss of experience occurs after realizing \( q + R \) units (explanation of the symbols in the figure 1 description), the exponent of the forgetting curve \( f \) equals [26]:

\[
f = l \frac{\log q}{\log(q + R) - \log(q)}. (10)
\]

In their model called VRVF (Variable Regression Variable Forgetting Model) Carlson and Rowe [27] assumed that the exponent of the forgetting curve is changeable in the subsequent cycles and it is dependent on the number of realized units in a cycle.

Figure 1. The influence of knowledge acquisition and forgetting on the work efficiency [28]; \( t_p \) – time used to realize \( q \) units; \( t_h \) – the minimum time after which the total loss of the learning effect occurs, \( R \) – the number of potentially realized units in the case of no intervals, \( q_i (q+R) \) – respectively the
number of potentially produced units in the time $t_p$ and $(t_p + t_B)$, while $x \leq q + R$ and $t_{B} \leq t_{B}$.)

Jaber and Bonney \[26\] (Learn-Forget Curve Model – LFCM) proposed that the exponent value of the forgetting curve $0 \leq f_i \leq 1$ ought to be calculated using the following expression:

$$f_i = \frac{l(1-l)\log(u_i + n_i)}{\log(1 + \frac{D}{u_i + n_i})}; \; i = 1, 2, \ldots , (11)$$

where: $n$ – remembered experience at the beginning of the cycle $i$, resulting from the realization of the previous $i-1$ cycles, $D$ – duration of the interval which causes the total loss of experience, $u_i$ – the number of realized units in the cycle $i$, $t(u_i + n_i)$ – realization time $u_i + n_i$ of the units, which equals:

$$t(u_i + n_i) = \sum_{x=1}^{n} t_i (u_i + x)^{-i} \equiv \int_{0}^{\infty} x^{-i} dx = \frac{t_i}{1 - l(l(u_i + n_i))^{-i}}; \; i = 1, 2, \ldots . (12)$$

The major inconvenience of the LFCM model is the difficulty in determining the duration $D$, in which the total loss of acquired experience will occur.

Nembhard and Uzumeri \[30\] modified the proposition presented in Mazur and Hastie’s work \[23\] (expression (6)). In order to take account of the influence of multiple learn-forget cycles on the efficiency of the realized processes $w_n$, they proposed the following formula:

$$w_n = k\left(\frac{nR^{\alpha} + p}{nR^{\alpha} + p + r}\right), \; \alpha, w_n, k, p, n \geq 0, p + r > 0, (13)$$

where:

$$R_n = \frac{\sum_{i=1}^{n}(t_i - t_0)}{n(t_n - t_0)}, (14)$$

$t_0$ – completion time of the works in the first unit, $t_n$ – completion time of the works in the last $n$ unit (the works in these units are realized in a continuous mode), $t_i$ – the works completion time in the unit $i$, $\alpha$ – parameter of the model which reflects the forgetting ability for the individual processes.

The value $R_n$ reflects a partial loss of the acquired experience in the effect of work interval occurrences (recency of experiential learning). After an interval occurs, once the works are recommenced the time in the first unit will equal:

$$\bar{T}^{RC} = T_i\left(nR^{\alpha}ight)^{-i}. (15)$$

However, Nembhard and Uzumeri \[30\] failed to present an explanation to the assumed model (called the Recency Model) and the means to determine the parameter $\alpha$.

Globerson and Levin \[31\] proposed an easily applicable model, in which the forgetting effect is directly dependent on the duration of an interval $\Delta t$:
where:

\[ t_w = \text{duration of the subsequent process}, \text{ if an interval does not occur}, \]
\[ a = \text{forgetting coefficient}, \]
\[ e = \text{the base for natural logarithms}. \]

Lam et al. [24] took account of the learn-forget curves while determining the commencement and completion times of the construction works within the projects planned with the Line of Balance Method. Lutz et al. [32] used the Wright model in the simulation studies of the construction projects. They assumed that due to the learning effect the duration times of construction projects may be reduced by 25% at maximum. Running simulation studies, Biruk and Rzepcki [33] showed that taking account of the learning curve theory may lead to a significant reduction of the expected completion time of a project, even if there is a lack of continuity in the works of construction crews and a partial loss of the acquired experience has occurred.

It is frequently assumed in these studies that the learning rate for most processes in the field of construction ranges between 70% and 90%. It mainly depends on the automation rate of the processes, management quality, working conditions improvements, implemented upgrades, motivational remuneration system and workers’ learning abilities.

While analyzing reinforcement works conducted in 21 buildings, Jarkas [34] found that it is not always possible to observe a performance boost resulting from repetition. Studying the efficiency of concreting works, Jarkas and Horner [35], observed that 18 out of the 45 analyzed buildings have displayed a performance drop when the number of completed levels was increased. 26 of them showed an increase lower than 1%, while only one showed an increase of 5%.

The observed lack of boost in performance with an increased number of repetitions or even a drop in performance may result from multiple factors: workers’ tiredness, absence from work, lack of a motivational remuneration system, high personnel fluctuation and frequent changes within construction crews, increased workloads related to the transportation of products to higher levels or use of improper tools [35], [36].

The changeability of working conditions at a construction site hinders direct adaptation of the methods and techniques applied in industrial production to the field of construction.

3. The implementation of a schedule taking account of the learning-forgetting effect in the MS Excel software

Functions of the MS Excel software calculating spreadsheet were used in order to present a model of the problem in a form that is customary for practitioners, as well as to show the effect of learning and forgetting on the duration of repetitive construction processes. The model involves an analysis of the effect of learning and forgetting on the completion time of finishing works in a 10-storey residential building. On each level there are 5 consecutively realized construction processes: partitioning with the use of aerated concrete blocks, plastering, preparing the basis under the floor, painting and laying floor layers (table 1). It was assumed that the amount of work necessary to complete the works on each level is equal, whereas the efficiency of the construction crews is conditioned by the efficiency of machines (it cannot be modified in a continuous way), which results in a variety of completion times of the consecutive works in the same construction unit. It was assumed that the processes are commenced at times \( t^r_{ij} \) which are the earliest possible (directly after the completion of a previous process in the unit and the completion of works in the previous unit) according to the relation:

\[
t^r_{ij} = \max\left( t^r_{(i-1),j} + t_{(i-1),j}, t^r_{(j-1),i} + t_{(j-1),i} \right),
\]

(17)
where: \( t_{ij} \) is the duration of the works of the first crew \( i (i = 1, 2, \ldots, 5) \) in the unit \( j (j = 1, 2, \ldots, 10) \) and \( r'_{11} = 0 \). The adopted assumptions lead to the occurrence of intervals in the works of the construction crews.

Table 1. Durations of construction processes conducted on each floor

| Process           | Duration \( t \) [days] |
|-------------------|------------------------|
| Partition walls (P1) | 10                     |
| Plasters (P2)     | 8                      |
| Backings (P3)     | 9                      |
| Painting (P4)     | 4                      |
| Floors (P5)       | 7                      |

In the proposed method, Wright’s exponential model of learning – the expression (1) – as well as the forgetting model prepared by Globerson and Levin – the expression (16) – were applied.

Two finishing works realization schedules were prepared according to the proposed method. The first of them does not take account of the duration time modifications resulting from the learning-forgetting effect, in the same way that is found in commonly used software for construction works scheduling (figure 2). In this case, the completion time equalled 128 days. However, in the other approach, which takes account of the effect of learning and forgetting, it was assumed that the learning rate and the forgetting coefficient are the same for each process and they equal respectively \( s = 0.9, a = 0.15 \). Under such conditions, the completion time equalled 104 days (figure 3). Therefore, the reduction in the duration thanks to the learning-forgetting effect in the case of this project equaled 24 days.

Figure 2. Project schedule without learning-forgetting effect
4. Conclusions
Studying the effects of experiencing and forgetting as well as the dispersion of the duration times of repetitive processes should be among the fields of interest for the scientists and practitioners related to the construction industry, as it enables a more precise estimation of realization times for construction projects. The conducted studies indicate that taking account of this effect leads to a significant reduction of the expected directive time of a project, even in the case of the lack of continuity in the works of construction crews and partial loss of acquired experience. The observed effect of performance boost leads to reaching the same goals with the engagement of lesser means. It would be advisable to create databases containing information about the learning rates reached during various construction works. These could prove helpful while realizing construction projects and preparing bidding plans. The usefulness of the gathered data may be limited, as the learning effect is highly dependent on the construction realization conditions. It is crucial to take account of the constant technological and organizational progress being made in the field of construction as well.

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References
[1] I. Łapuńka, K. Marek-Kołodziej, and I. Pisz, “Pragmatism of Learning and Experience Curves in the Aspect of Project Organizations,” Przedsiębiorczość i Zarządzanie, no. t. 16, z. 5, cz. no.2 Determinanty zarządzania projektami i procesami w organizacji, pp. 29–41, 2015 (in Polish).
[2] D. J. Harmelink and J. E. Rowings, “Linear scheduling model: development of controlling activity path,” Journal of Construction Engineering and Management, vol. 124, no. 4, pp. 263–268, Jul. 1998.
[3] G. Lucko, “Productivity scheduling method compared to linear and repetitive project scheduling methods,” Journal of Construction Engineering and Management, vol. 134, no. 9, pp. 711–720, Sep. 2008.
[4] J. J. O’Brien, “VPM scheduling for high-rise buildings,” ASCE J Constr Div, vol. 101, no. 4, pp. 895–905, 1975.
[5] R. B. Harris and P. G. Ioannou, “Scheduling projects with repeating activities,” *Journal of Construction Engineering and Management*, vol. 124, no. 4, pp. 269–278, Jul. 1998.

[6] W. Y. Thabet and Y. J. Beliveau, “HVLS: Horizontal and Vertical Logic Scheduling for Multistory Projects,” *Journal of Construction Engineering and Management*, vol. 120, no. 4, pp. 875–892, Dec. 1994.

[7] M. A. Ammar, “LOB and CPM Integrated Method for Scheduling Repetitive Projects,” *Journal of Construction Engineering and Management*, vol. 139, no. 1, pp. 44–50, Jan. 2013.

[8] H. R. Zolfaghar Dolabi, A. Afshar, and R. Abbasnia, “CPM/LOB Scheduling Method for Project Deadline Constraint Satisfaction,” *Automation in Construction*, vol. 48, pp. 107–118, Dec. 2014.

[9] Y. Tang, R. Liu, and Q. Sun, “Schedule control model for linear projects based on linear scheduling method and constraint programming,” *Automation in Construction*, vol. 37, pp. 22–37, Jan. 2014.

[10] P. Jaśkowski and M. Tomczak, “Assignment problem and its extensions for construction project scheduling,” *Czasopismo Techniczne*, vol. 2014, no. Budownictwo Zeszyt 2-B (6) 2014, pp. 241–248, Jun. 2014.

[11] Y. Su and G. Lucko, “Linear scheduling with multiple crews based on line-of-balance and productivity scheduling method with singularity functions,” *Automation in Construction*, vol. 70, pp. 38–50, Oct. 2016.

[12] P. Jaśkowski and S. Biruk, “Scheduling repetitive construction processes,” *Zeszyty Naukowe / Wyższa Szkoła Oficerska Wojsk Lądowych im. gen. T. Kościuszy*, vol. Nr 3, 2014 (in Polish).

[13] E. Radziszewska-Zielina and B. Sroka, “Priority Scheduling in the Planning of Multiple-Structure Construction Projects,” *Arch. Civ. Eng.*, vol. 63, no. 4, pp. 21–33, Dec. 2017.

[14] S. Biruk and P. Jaskowski, “Scheduling Linear Construction Projects with Constraints on Resource Availability,” *Arch. Civ. Eng.*, vol. 63, no. 1, pp. 3–15, Mar. 2017.

[15] R. Pellegrino, N. Costantino, R. Pietroforte, and S. Sancilio, “Construction of multi-storey concrete structures in Italy: patterns of productivity and learning curves,” *Construction Management and Economics*, vol. 30, no. 2, pp. 103–115, Feb. 2012.

[16] A. Panas and J. P. Pantouvakis, “Simulation-Based and Statistical Analysis of the Learning Effect in Floating Caisson Construction Operations,” *Journal of Construction Engineering and Management*, vol. 140, no. 1, p. 04013033, Jan. 2014.

[17] L. Mályusz and A. Pém, “Prediction of the learning curve in roof insulation,” *Automation in Construction*, vol. 36, pp. 191–195, Dec. 2013.

[18] R. Davis, “Teaching Note—Teaching Project Simulation in Excel Using PERT-Beta Distributions,” *INFORMS Transactions on Education*, vol. 8, no. 3, pp. 139–148, May 2008.

[19] F. A. E.-M. Agrama, “Linear projects scheduling using spreadsheets features,” *Alexandria Engineering Journal*, vol. 50, no. 2, pp. 179–185, Jun. 2011.

[20] T. P. Wright, “Factors Affecting the Cost of Airplanes,” *Journal of the Aeronautical Sciences*, vol. 3, no. 4, pp. 122–128, 1936.

[21] J. G. H. Carlson, “Cubic learning curves-precision tool for labor estimating,” *Manufacturing Engineering & Management*, vol. 71, no. 5, pp. 22–25, 1973.

[22] J. R. DeJong, “The Effects of Increasing Skill on Cycle Time and Its Consequences for Time Standards,” *Ergonomics*, vol. 1, no. 1, pp. 51–60, Nov. 1957.

[23] J. E. Mazur and R. Hastie, “Learning as accumulation: a reexamination of the learning curve,” *Psychol Bull*, vol. 85, no. 6, pp. 1256–1274, Nov. 1978.

[24] K. C. Lam, D. Lee, and T. Hu, “Understanding the effect of the learning–forgetting phenomenon to duration of projects construction,” *International Journal of Project Management*, vol. 19, no. 7, pp. 411–420, Oct. 2001.

[25] S. Globerson, N. Levin, and A. Shtub, “The Impact of Breaks on Forgetting When Performing A Repetitive Task,” *IEE Transactons*, vol. 21, no. 4, pp. 376–381, Dec. 1989.
[26] M. Y. Jaber and M. Bonney, “Production breaks and the learning curve: The forgetting phenomenon,” *Applied Mathematical Modelling*, vol. 20, no. 2, pp. 162–169, Feb. 1996.

[27] J. G. Carlson and A. J. Rowe, “How much does forgetting cost?,” *Industrial Engineering*, vol. 8, no. 9, pp. 40–47, 1976.

[28] M. Y. Jaber and M. Bonney, “A comparative study of learning curves with forgetting,” *Applied Mathematical Modelling*, vol. 21, no. 8, pp. 523–531, Aug. 1997.

[29] S. E. Elmaghraby, “Economic manufacturing quantities under conditions of learning and forgetting (EMQ/LaF),” *Production Planning & Control*, vol. 1, no. 4, pp. 196–208, Oct. 1990.

[30] D. A. Nemhbad and M. V. Uzumeri, “Experiential learning and forgetting for manual and cognitive tasks,” *International Journal of Industrial Ergonomics*, vol. 25, no. 4, pp. 315–326, May 2000.

[31] S. Globerson and N. Levin, “Incorporating Forgetting into Learning Curves,” *Int Jnl of Op & Prod Mnagement*, vol. 7, no. 4, pp. 80–94, Apr. 1987.

[32] J. D. Lutz, D. W. Halpin, and J. R. Wilson, “Simulation of Learning Development in Repetitive Construction,” *Journal of Construction Engineering and Management*, vol. 120, no. 4, Issue: object: doi: . /jcemd4.1994.120.issue-4, revision: rev:1479261261584-18364:doi:10.1061/jcemd4.1994.120.issue-4 1061.

[33] S. Biruk and Ł. Rzepecki, “The impact of learning–forgetting phenomenon on duration of repetitive construction processes conducted in random conditions,” *Przegląd Naukowy Inżynieria i Kształtowanie Środowiska*, vol. 2017, no. vol.26(2), pp. 202–209, May 2017 (in Polish).

[34] A. M. Jarkas, “Influence of Buildability Factors on Rebar Installation Labor Productivity of Columns,” *Journal of Construction Engineering and Management*, vol. 138, no. 2, pp. 258–267, Feb. 2012.

[35] A. M. Jarkas and M. Horner, “Revisiting the applicability of learning curve theory to formwork labour productivity,” *Construction Management and Economics*, vol. 29, no. 5, pp. 483–493, May 2011.

[36] A. M. Jarkas, “The Effects of Buildability Factors on Rebar Fixing Labour Productivity of Isolated Foundations,” *International Journal of Construction Management*, vol. 10, no. 2, pp. 33–51, Jan. 2010.