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Construction Work Execution Simulation Using System Dynamics: Case of the Wawel Castle Courtyard

Symulacja cyklu realizacji roboty budowlanej w oparciu o model Dynamiki Systemów. Przypadek Dziedzińca Zamku Królewskiego na Wawelu

Keywords: complex systems, systems thinking, System Dynamics, risk, construction works

Słowa kluczowe: systemy złożone, myślenie systemowe, Dynamika Systemów, ryzyko, roboty budowlane

Introduction

Current trends in planning construction projects that target heritage sites feature an intense development of methods of planning for conditions of risk and uncertainty. The vast majority of planning approaches, ranging from project cycles to cost analysis, are based on network theory. So-called task networks, either in single- or two-point notation, are used to model projects. The logical structure of such networks defines the technological and organizational relations between a project's tasks (construction works). Apart from a project's logical structure, the model defines functions, which are noted on the nodes and links of these networks, and specify the parameters (e.g., execution time and cost, material usage) of each construction work. Assessing these parameters often comes down to using Delphi methods, and the use of: standard databases, theoretical probability distributions (e.g., beta or Gauss distribution), or fuzzy logic elements. Numerous methods have been developed to analyze such network models, with major ones being: CPM (Critical Path Method), PERT (Program Evaluation and Review Technique), GERT (Graphical Evaluation and Review Technique), and CCPM (Critical Chain Project Management).

However, most of these approaches to assessing a planned project's essential parameters consider neither their complexity at the level of specific works nor the role of emergent properties as responses to risk factor impacts and their consequences. The effective estimation of the time or cost of performing a given work requires investigating essential, dynamic and often non-linear relations between its elements as a system (people, materials, equipment, etc.) and their interactions with the external environment [Zhu 2016]. In the literature we can find examples of the application of so-called systems thinking to analyze construction works treated as complex systems, whose interlinked and interacting elements are oriented towards achieving specific goals [Zhu 2016]. Despite this, most of the literature presents qualitative approaches to analyzing complex systems in the construction sector. The few

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quantitative approaches are essentially based on Discrete Event Simulation (DES) or Agent-Based Modelling (ABM). Notably, System Dynamics (SD) is an essential approach in systems thinking. Over the past five years, SD has enjoyed increasing interest among researchers in construction management [Xu, Zou 2021; Sirovs 2022].

This interest is visible primarily in areas such as: construction project planning and control, and the management of the associated risk, workplace health and safety, and resources, organizational performance analysis, and investigating projects conducted as public–private partnerships (PPP) [Xu, Zou 2021].

Estimating essential parameters such as project execution time and cost while considering risk, especially risk specific to heritage sites, is an important area of research. The majority of the literature on this application of System Dynamics focused on singular risk factors such as: critical weather conditions [Boateng, Chen, Ogunlana 2012] or resource supply problems [Park 2005] which affect these parameters. However, there are few comprehensive models that consider the complementary nature of these impacts [Nasirzadeh, Nojedehi 2013]. It should also be noted that these approaches are mostly used to analyze complex systems at the project level [Zhu, Mostafavi, Ahmad 2014] and there are very few approaches that enable studying the behavior of such systems at task level.

The objective of this study was to develop a general model of a system's dynamics and to use it to analyze the execution time and costs. of a single construction work. The model features essential risk factors that determine construction crew performance, such as: worker absenteeism due to sick leaves, construction equipment failures, material availability problems, poor weather conditions or poor work quality assurance [Dawood 1998], within which the authors considered faulty workmanship and the effects of learning on construction personnel performance. The application potential of the proposed approach has been presented using a case of applying a wearing course layer to a shared space located in the Outer Courtyard of the Wawel Royal Castle. The authors wish to note that the universality of the simulation model can be used to estimate the time and costs of performing typical construction works while considering the abovementioned essential risk factors.

System complexity

As per general systems theory, a system is understood as a set of elements and relations between these elements, oriented towards achieving a specific goal [von Bertalanffy 1951; Meadows 2008]. Construction projects are complex systems as co-dependent, non-linear and dynamic interactions take place between their elements and their external environments, and their objective is to build a new structure or to maintain a pre-existing structure in good condition [Zhu 2016].

Essentially, a project's (system's) complexity can be divided into two types [Hetogh, Westerveld 2010; Senge 2006]: detail complexity, which is independent of time and stems from the system's own structure, and dynamic complexity, which changes over time and is the effect of the system's various difficult-to-predict operational behaviors, which are often non-linear and have cause-and-effect relationships. Understanding the behavior of a complex system demands its analysis as a whole, instead of its individual, deconstructed elements. Each change in a given part of a system (e.g., caused by risk factors) can, via propagation, lead to unforeseen effects in another part. Feedback loops in interelement relations, which mean that the result of a given behavior can also become its cause, play a significant role in a system's behavior [Żukowski 2012]. It should be remembered that in complex systems, due to feedback loops, any disruptions (as a result of delays in communication) may be difficult to address at the moment they are encountered [Meadows 2008]. One key characteristic of complex systems are their emergent properties, which stem from the co-dependent and dynamic relationships between their elements [Zhu 2016]. These properties are the system's response to external impacts and the disruptions caused by them. In the literature we can find examples of various emergent properties, such as: vulnerability to external factors, adaptive capacity to changing project conditions [Zhu, Mostafavi 2017] and others. Assessing complex systems' emerging properties is key to understanding how they behave when interacting with external environments.

Risk factors specific to heritage sites

Projects involving heritage sites have their own specific risk factors which can severely impact their execution schedules and thus overall cost. These include, but are not limited to: discoveries of artifacts or architectural features that merit additional investigation and conservation, incorrect assumptions as to the static behavior or material composition of structural elements, or the discovery of additional, previously undocumented elements of a building [Radziszewska-Zielina et al. 2018]. These occurrences may and sometimes do cause a near-complete overhaul of a project or its outright cancellation. It is therefore crucial to adopt a proactive approach in planning such projects to account for their additional uncertainties and risks, whose materialization may significantly impact key project indicators [Śladowski 2022].

System Dynamics

System Dynamics is a concept of modelling complex systems and their continuous simulation, developed towards the end of the 1950s by a team directed by J.W. Forrester from the Massachusetts Institute of Technology [Forrester 1958]. System Dynamics, as a concept, is underpinned by so-called systems thinking, which identifies cause-and-effect relationships, includ-

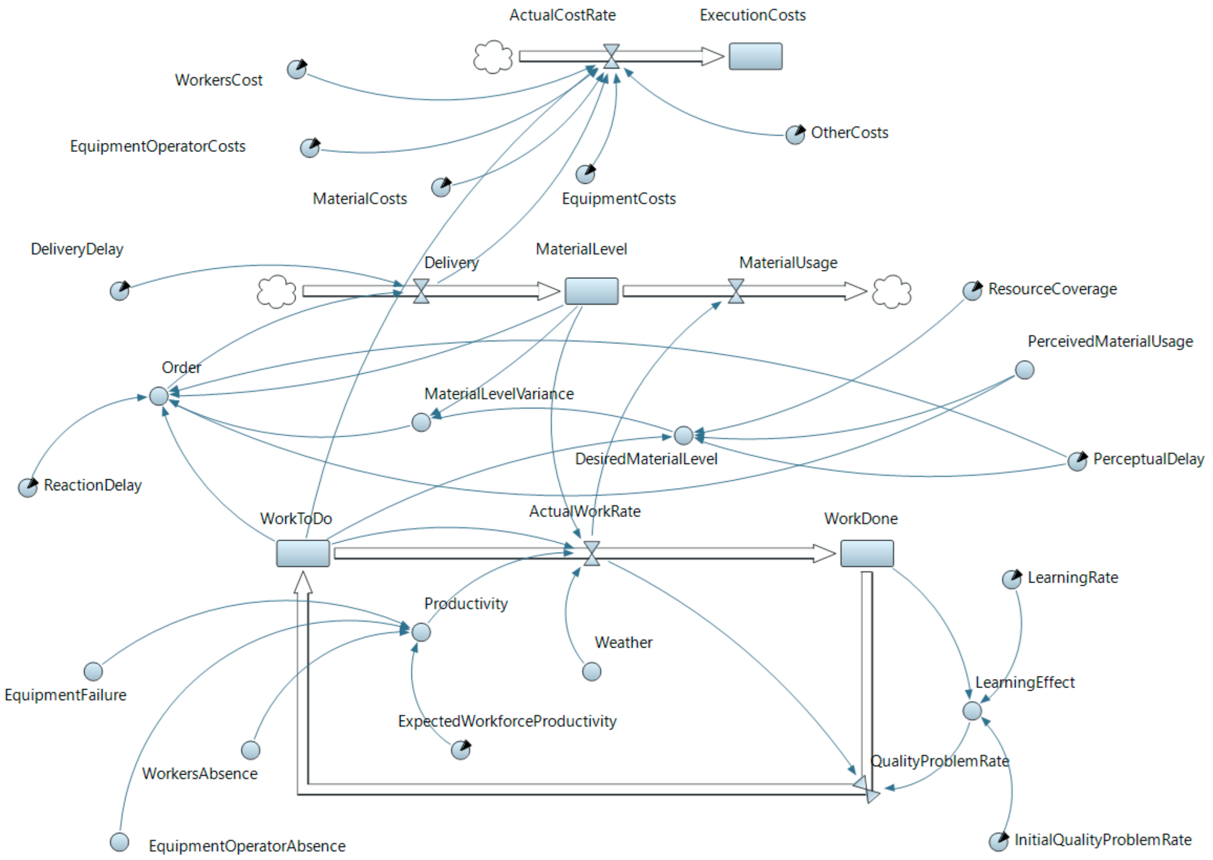

Fig. 1. Flow diagram of the main system dynamics model, built to analyze the execution of a construction work; all graphs by the authors

Ryc. 1. Diagram przepływowy ogólnego modelu dynamiki systemu do analizy cyklu realizacji roboty budowlanej; wszystkie schematy przygotowane przez autorów

ing feedback loops, between a complex system's elements, which determine its behavior [Sterman 2000; Łatuszyńska 2015]. At the initial stage of a system's modelling, causal-loop diagrams are created, which present the general structure and dependencies within the system. Quantitative system dynamics analysis is based on so-called flow diagrams, which describe a system using levels and flows [Kwaśnicki 1998]. To model the system's structure using a flow diagram, three main variable types are used [Łukaszewicz 1975; Hoffmann, Protasowicki 2013]: level, which defines the state/value/quantity of a given system element at a specific point in time, flow, which defines the speed with which level values change, and ancillary variables, which allow us to regulate flow depending on information about a system's state at a given time.

The dynamics of how these variables change depends on two types of competing feedback loops: the positive feedback loop, which is also called self-reinforcing feedback, and the negative feedback loop, also called balancing feedback.

The consequence of the abovementioned modelling is the construction of calculus equations that determine the system's behavior over time. In many computer programs dedicated to modelling and simulating using System Dynamics, the calculus equation sets are built automatically upon entering flow diagram parameters. A model's equations are saved in a discretized form in this case, and time is denoted as t, while the variable dt denotes the timespan with which the equations are integrated. The value of each level at time t is equal to the value of this level at time $(t - 1)$, increased by the difference between the values of what flows in and what flows out of it during timespan *dt*.

Main model

The model of a typical construction work's dynamics as a system presented in this paper considers interdependent relations between its elements and factors that affect them. The simulation analysis of the model allows not only for estimating the execution time and costs of a given work, but also collecting essential data on its behavior as a system under specific conditions and identifying its weaknesses. The model's flow diagram, presented below (Fig. 1), was built in AnyLogic and includes typical risk factors, as listed in the introduction [Dawood 1998], that disrupt the execution of construction works, which forms a basis for its extension and adaptation over the course of analyzing specific construction works performed under project-specific conditions.

Model sections

Below is a listing and overview of each component of the model. As the components correspond to elements used in AnyLogic, the names of these components have been paired with how they appear in the program, with the name used in AnyLogic written in parentheses.

Expected workforce productivity

Expected workforce productivity (ExpectedWorkforceProductivity) is defined in the model as the number of production units (pieces, m, m^2, m^3, kg, etc.) that should be produced/completed under average technological and organizational working conditions per unit of time (workday). Expected productivity can be calculated as the reciprocal of the working time per production unit standard [Hoła, Mrozowicz 2003]. The work time standard includes standard time, which is spent on production, and complementary time, excluding any possible time loss, namely non-standard time as a result of disruptions such as: poor weather conditions, absenteeism due to sick leaves, equipment failures, etc. [Lawrance, Petrides, Guerry 2021]. In the model, Expected workforce productivity affects a construction crew's Productivity.

Execution Costs

The costs of executing a construction work (ExecutionCosts) are determined based on the assumed expected value of per-unit direct costs, which include labor (WorkersCost), equipment (EquipmentCost) and its operation (EquipmentOperatorCost) per unit of time (workday), and materials (MaterialCosts) per their respective natural units (per piece, m, m^2, m^3, kg, etc.). Apart from direct costs, the model features other types of per-unit costs (OtherCosts), such as indirect costs. The model assumes that the value of direct labor and equipment per-unit costs is constant, regardless of daily output, which is variable (due to risk factor impact). Material cost is the product of the per-unit cost of materials and their amount delivered to the construction site (Delivery).

Material coverage

Material coverage problems were considered as based on the supply model presented in [Hertogh, Westerveld 2010]. It presents changes in material supply levels at the site depending on current usage and supply. In the model, it was assumed that material supplies should cover demand for a specific number of days—expressed as resource coverage (ResourceCoverage). This is due to the fact that it is not possible to precisely plan ongoing resource usage, which is why it will never perfectly align with material deliveries. In addition, there can be delays in deliveries themselves. A certain surplus in material levels at the site is therefore desirable. Higher material usage will carry over to a higher desired material level (DesiredMaterialLevel). The discrepancy between actual and desired material level—material level variance (MaterialLevelVariance)—will also be greater, which can lead to increasing order volume. Therefore, we can identify a balancing usage feedback loop in the model, which lowers the material level, and a balancing delivery feedback loop, which resupplies material levels.

The model was built to include three delay types:

- Perceptual delay (PerceptualDelay), which is deliberate. As a result of this delay, decisions concerning Orders are made not on the basis of usage for a given day, but based on average usage from a defined period (perceptual delay). It is intended to reduce the impact of acute swings in the trend of actual material usage.
- Reaction delay (ReactionDelay), which is also deliberate. In a situation where there is a discrepancy between actual and desirable material levels, the ordering party, instead of compensating with a single order, submits an order that covers the discrepancy to a level equal to the discrepancy divided by the reaction delay. Thus, the party distributes the order size over time to be certain that the identified material usage trend is true.
- Delivery delay (DeliveryDelay), which is independent of the party placing the order, and is associated with processing, preparation and delivery of the order by the supplier. It is necessary to define the initial order volumes (before those based on actual usage will start being delivered) or ensuring sufficient initial material levels.

The desired material level and order volume should be account for the volume of work that is left to complete and previous orders that have not yet been delivered, so as not to order material when work is approaching finalization and existing material levels and previous orders should cover the demand.

Worker absence

Human resource availability problems translate as employee absenteeism due to sick leave, and is broadly defined as failure to come to work due to poor health and is an ever-present problem that disrupts business operations and generates economic cost [Lawrance, Petrides, Guerry 2021]. Absence due to sick leave may be caused by a person becoming ill themselves or having to care for a sick child or other family member, and is documented by a medical professional who certifies the employee's temporary inability to work [Zakład Ubezpieczeń Społecznych 2011]. In the model, the impacts of worker (WorkersAbsence) and equipment operator absence (EquipmentOperatorAbsence) were considered based on an employee attendance prognosis for every analyzed workday and the resultant change in the crew's productivity.

Equipment failure

Equipment failure is a problem considered to be a part of renewable resource availability. The usability of the set of construction equipment, apart from the indi-

Fig. 2. Satellite image of Wawel Castle, with the scope of the work modelled outlined in red; source: original work based on an image from Google Maps, 2025

Ryc. 2. Zdjęcie satelitarne Zamku Królewskiego na Wawelu, z zakresem modelowanej roboty oznaczonym na czerwono; źródło: opr. własne na podstawie obrazu z Google Maps, 2025

vidual piece's failure rate, may depend on the adopted reliability structure and the so-called equipment reserve [Jaworski 1999]. In the model, equipment failure (EquipmentFailure) was considered as a prognosis of equipment count in every analyzed workday and the resultant change in productivity.

Weather

In the case of construction work that is vulnerable to critical weather conditions (Weather), a crew's productivity is corrected based on historical data for weather profiles in the period the project was executed in.

Workmanship quality and employee learning model

Learning models used in the construction sector can be used to analyze the productivity of human resources engaged in executing works. An analysis of productivity increases is justified especially when uniform construction works are performed, when construction workers improve their abilities due to experience [Łapuńka, Pisz, Marek-Kołodziej 2015; Biruk, Rzepecki 2017]. The continued repetition of processes can not only enhance employee productivity, but also enhance workmanship quality, minimizing the number of corrections which in the model are generated by the quality problem rate flow (QualityProblemRate). In the literature we can find numerous learning models that are also used in construction, and some of these also account for the effect of forgetting [Saravana Prabhu, Vidjeapriya 2021]. In this paper, the authors used the simplest learning curve model developed in [Wright 1936]. This model was adapted to the analysis of quality problem rate as a result of learning (LearningEffect), represented in the model by the learning rate, which contributes to minimizing initial quality problem rate (InitialQualityProblemRate) as a result of employees adapting to design requirements that affect the quality problem rate (QualityProblemRate).

The discretized equations for the proposed main model, adapted to the programming language used in AnyLogic, can be shared by the authors upon request.

Case presentation

To present the proposed approach, the authors used a construction work in which a stone tile wearing course was laid as a part of the project named: Reconstruction and improvement of the state of immovable monuments and enhancement of the quality of services for national and foreign tourists as a part of the popularization of global cultural heritage, conducted as a part of "Priority XI of the Infrastructure and Environment Operational Program, action 11.1 'Protec-

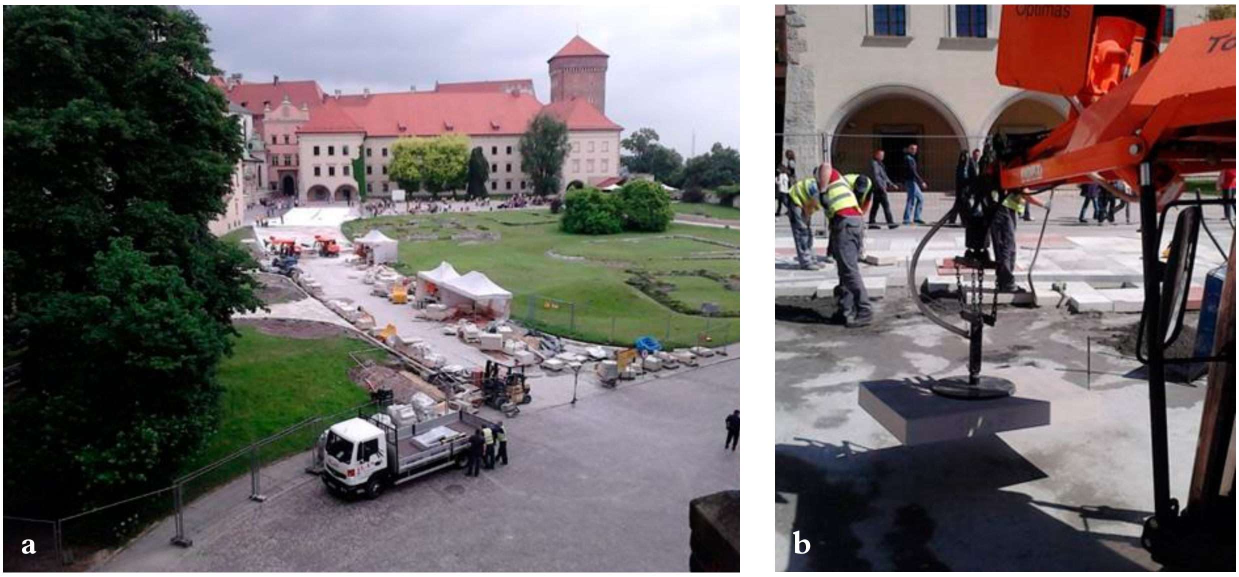

Fig. 3. Road work involving the laying of a stone tile wearing course: a) view of the site, b) self-propelled vacuum lifter with a hydraulic suction mechanism for the transport of stone tiles across the site; all photos by G. Śladowski

Ryc. 3. Robota drogowa związana z układaniem warstwy ścieralnej nawierzchni z płyt kamiennych: a) widok placu budowy, b) wózek samojezdny z przyssawką hydrauliczną do transportu płyt kamiennych w obrębie placu budowy; wszystkie zdjęcia autorstwa G. Śladowskiego

Fig. 4. Stone tile cutting stations and storage area, limited due to the historic environment and the continued use of the historic site by tourists

Ryc. 4. Stanowiska docinania płyt i ich składowania, ograniczone z powodu zabytkowego otoczenia i równoległego użytkowania obszaru zabytkowego przez turystów tion and preservation of cultural heritage of superregional significance'." The scope of the work itself has been presented in Figure 2.

The work discussed in this paper is a fragment of a larger project that featured the renovation of the entirety of the pavements of the outer courtyard, including a reinforcement of the inner side of the Austrian-period fortifications. Multiple significant archaeological discoveries were made during the project's execution, including: the foundations of the royal stables, the foundations of the Tęczyn Tower, fragments of a gate wall in the defensive embankment, fragments of stone pavement from various period, and a Nazi-occupation-period fuel tank.

Overview of the Wawel Royal Castle

The Wawel Royal Castle can be considered Poland's pre-eminent monument and the definitive symbol of Polish royalty, as it served as the official seat of Polish kings from the late eleventh century to 1611, when King Sigismund III Vasa decided to permanently move his court to Warsaw. The first traces of settlement at Wawel Hill, the site of the castle, are dated to the fourth century CE. The hill, as an easily defensible position located on an otherwise flat, marshy plain and partially blocked off by the Vistula's riverbed, became the site of a gord (fort) used by the ruling elite of Cracow and the nearby *suburbium* named Okół. Over time, the castle expanded, evolved and came to feature numerous historic buildings, including the Archcathedral Basilica of Saint Stanislaus and Saint Wenceslaus, Sigismund's Chapel, the Inner Courtyard and its arcade, as well as its imposing eighteenth- and nineteenth-century fortifications, which made it a part of the noyau (core) of Festung Krakau. Overviews of the history of the Wawel Royal Castle has been presented by Skowron [2001] and Franaszek [1988], whereas the role of the castle in the urban development of Cracow was discussed by Motak [2019].

Overview of the work subjected to modeling

The presented scope of work concerned a shared space with an area of 948 m^2, which was executed in the period between May 18, 2011, and July 8, 2011. One construction crew was involved in this work. The crew, apart from a complement of workers, was equipped with two self-propelled vacuum lifters for the transport of stone tiles and two stonecutting stations equipped with saws (Fig. 3). The work was vulnerable to a range of factors that determined its pace. First, due to organizational considerations (work on an operating facility), the contractor had limited space to store construction materials, which required careful control of material and deliveries. Another key factor were problems with settling on design requirements for the final layout of stone tiles on a surface with an arched boundary. Aspects such as vulnerability to poor weather conditions, absence due to sick leave or equipment failures also had to be factored in [Dawood 1998].

Input data

For the purposes of analyzing the model, the following input data was prepared.

Desired crew productivity

The desired number of production units q produced within time unit t, namely the construction of the wearing course made of stone tiles, can be calculated based on the following dependency:

$$q = \frac{t \cdot l_w \cdot h_d}{N_w} \qquad (1)$$

In addition, based on the set time standard for the leading unit, we can determine the number of ancillary units:

$$l_p = \frac{N_p}{N_w} \qquad (2)$$

To determine the work time unit for the leading unit and ancillary units, we used data published in material expenditure catalogues. The work time standard for the leading unit (self-propelled vacuum lifter) was calculated individually as equal to 0.42 man-hours per production unit, namely 1 m^2, of the stone tile wearing course. For a predetermined crew composition (4 pavers, 2 self-propelled vacuum lifters and 2 stone tile cutting stations) and an 8-hour workday, a daily crew productivity rate of 38.10 m^2 was obtained.

Execution Costs

The daily cost of labor for a crew of 6 workers (WorkersCost and EquipmentOperatorCost) was set at 17 PLN/h as per the costing publications for the second quarter of 2009 and an assumed eight-hour workday, which amounts to 816 PLN per day. The daily cost of equipment EquipmentCost) is specified by its per-day rental cost, which is 250 PLN for a self-propelled vacuum lifter and 120 PLN for a stone saw. Assuming two pieces of both types of this equipment, the per-day equipment cost was set at 740 PLN. The per-day material costs (MaterialCosts) were the product of the number of square metres of every batch of material delivered to the construction site and an assumed per-unit price of 750 PLN/m^2.

Other costs (OtherCosts) were the daily indirect costs set based on an indirect cost coefficient of 80% for the period under analysis and were based on the per-day costs of labor and equipment. These per-day costs amounted to 1,244.80 PLN.

Employee absenteeism

One of the essential measures of absenteeism used in businesses is the absenteeism indicator which is calculated using the equation below:

$$W_a = \frac{l_{da}}{l_z \cdot l_d} \qquad (3)$$

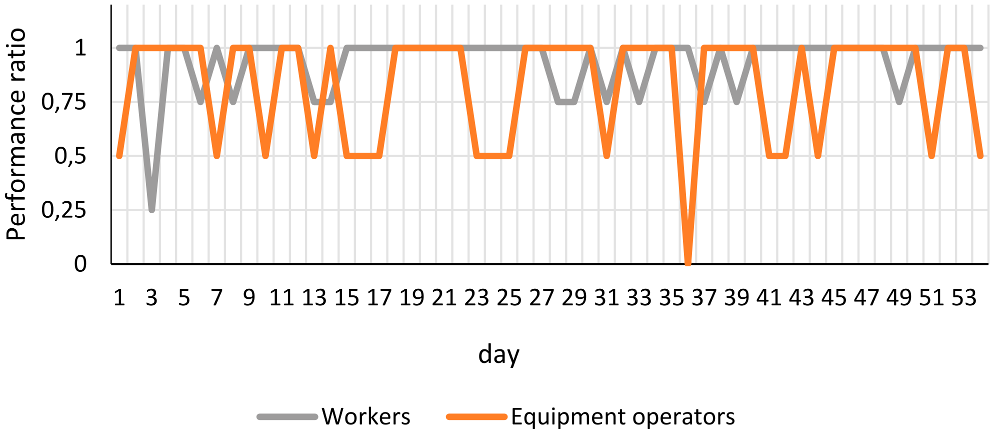

Fig. 5. Profile of the impact of worker absence due to sick leave on the performance of the construction crew on each day

Ryc. 5. Profil wpływu absencji chorobowej pracowników na wydajność brygady roboczej w poszczególnych dniach

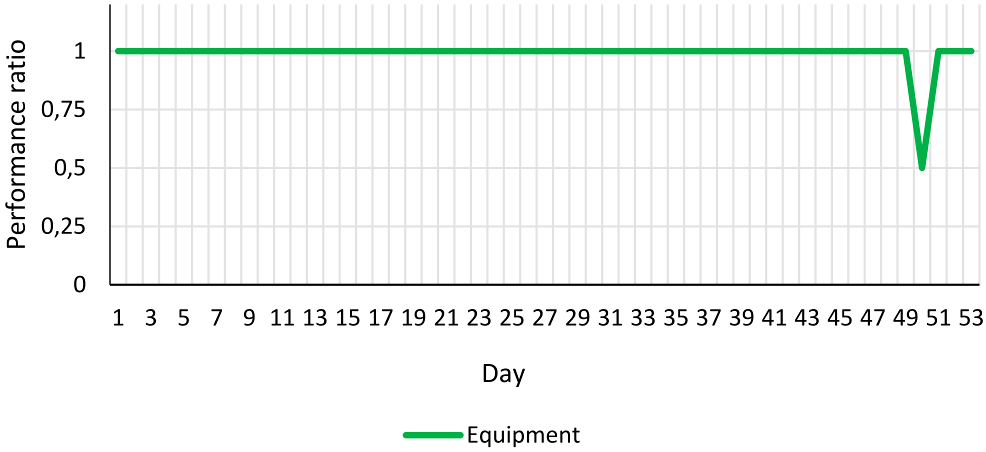

Fig. 6. Profile of equipment failure rate impact on crew productivity for each day

Ryc. 6. Profil wpływu awarii maszyn na wydajność brygady roboczej w poszczególnych dniach

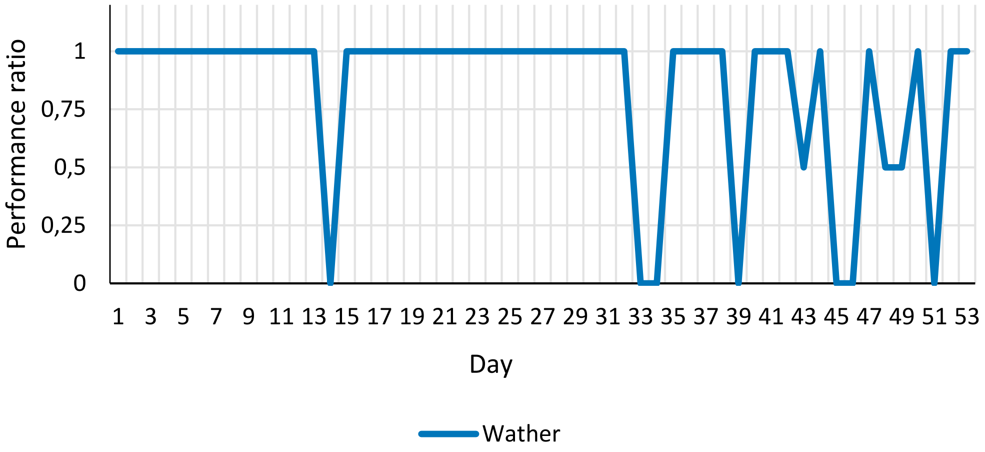

Fig. 7. Profile of equipment failure rate impact on crew productivity for each day

Ryc. 7. Profil wpływu intensywności opadów na wydajność brygady roboczej w poszczególnych dniach

Data on absenteeism was taken from publications of the Polish Social Security Office. The Office reported that in 2011 the sick leave register had 18,878.1 thousand entries listing temporary inability to work, totaling 246,736.7 thousand days of sick leave [Zakład Ubezpieczeń Społecznych 2011a]. It also listed an absenteeism indicator of 6.68% [Zakład Ubezpieczeń Społeczenych 2011b]. On this basis, we generated pseudo-random numbers which we used to create absence tables for every worker, and later collective absence tables for workers and equipment operators, which included simulated worker number ratios compared to the planned number of workers. These values have been presented in Fig. 5 and correct the productivity of the crew—measured as its performance ratio.

Equipment failure

To estimate the equipment failure rate of construction equipment, we can use the formula for the so-called average damage intensity, as found by Łapuńka, Pisz and Marek-Kołodziej [2015].

$$\lambda = \frac{\lambda_d t_{hd} + \lambda_r t_{hr}}{t_{hd} + t_{hr}} \tag{4}$$

Thus, for a layout of *N* pieces of equipment, the scheduled work and down time until the entire set fails can be determined using the following formula:

$$\tau_u = \frac{1}{\lambda} + \frac{1}{2\lambda} + \frac{1}{3\lambda} + \cdots + \frac{1}{N\lambda} \tag{5}$$

Using Eq. (4) and Eq. (5), we calculated the time to failure of the entire set of the two stone tile lifters, assuming (based on information from the contractor), that the failure intensity for a self-propelled vacuum lifter with a hydraulic suction cup during work was = 0.0035 and during downtime it was 0.0008. We assumed the planned equipment work time at = 6.5 hours and a downtime over an average work cycle of = 1.5 hours within an 8-hour workday. The rate was estimated for the simulated number of pieces of construction equipment for each day and corrected the productivity of each crew (Fig. 6). In the case of stone tile saw stations, the damage intensity was low enough that the failure rate of the saws was negligible and could be ignored within the work simulation investigated.

Weather

Due to the work being vulnerable to poor weather conditions, a daily atmospheric precipitation intensity profile was prepared based on historical data for Cracow in the period when the project was executed. The data was procured from https://meteomodel.pl/ which lists information from the Institute of Meteorology and Water Management – State Research Institute. The values, which correct the crew's performance, have been presented in Fig. 7.

Order logistics

Assuming effective logistics in terms of ordering materials by the contractor, the following values were entered into the model: an initial material level of 100 m^2, resource coverage for 5 workdays, perceptual delay of 7 workdays, reaction delay of 7 workdays, delivery delay of 7 workdays.

Workmanship quality and learning model

Due to the necessity to adjust the layout of the tiles on the shared space's surface to its arched boundary in plan view, the stone tiles had to be cut, which was not done in previous sections of the surface. These difficulties generated faults, which resulted in an initial quality problem rate of 0.05 and a learning rate of 0.9.

Analysis of results

A simulation analysis of the model was performed in AnyLogic. The result of the simulation of the proposed model of a construction work's execution time was 38 workdays (Fig. 8a) and is the same as the actual time (the work was executed in the period between 18.05.2011 and 08.07.2011), which signifies that the model is close to reality. In addition to time, information on the costs of executing the work was returned as well and equaled PLN 768,367.63 after 38 days. The productivity of the construction crew was determined not only by risk factors such as absence due to sick leave, weather or, to a lesser degree, equipment failure, but also by the aspect of usage (Fig. 8d) and order management. With the material supply parameters entered, we can identify periods (Fig. 8c) in which low material levels at the site prevented the full scope of the work from being done at a given crew productivity level. In addition, we can identify that around 30 m^2 of tiles was left unused co which generated additional cost. If works are not planned to continue over the course of further stages, such a surplus is undesirable. In terms of maintaining workmanship quality, it was possible to observe the learning effect (Fig. 8b), which contributed to a successive decrease in faulty work incidence.

The result of the simulation showed the system's behavior over time and revealed its weaknesses. The system can be optimized to minimize the construction work time and execution costs. To this end, material management can be improved by selecting suitable relevant parameters so that no material shortages will occur throughout the execution period. In terms of exposure to risk factors (such as employee absence, poor weather conditions, equipment failure, etc.) the optimization will be based on enhancing the system's resilience to these factors while using suitable strategies, such as redundancy and others [Śladowski 2022].

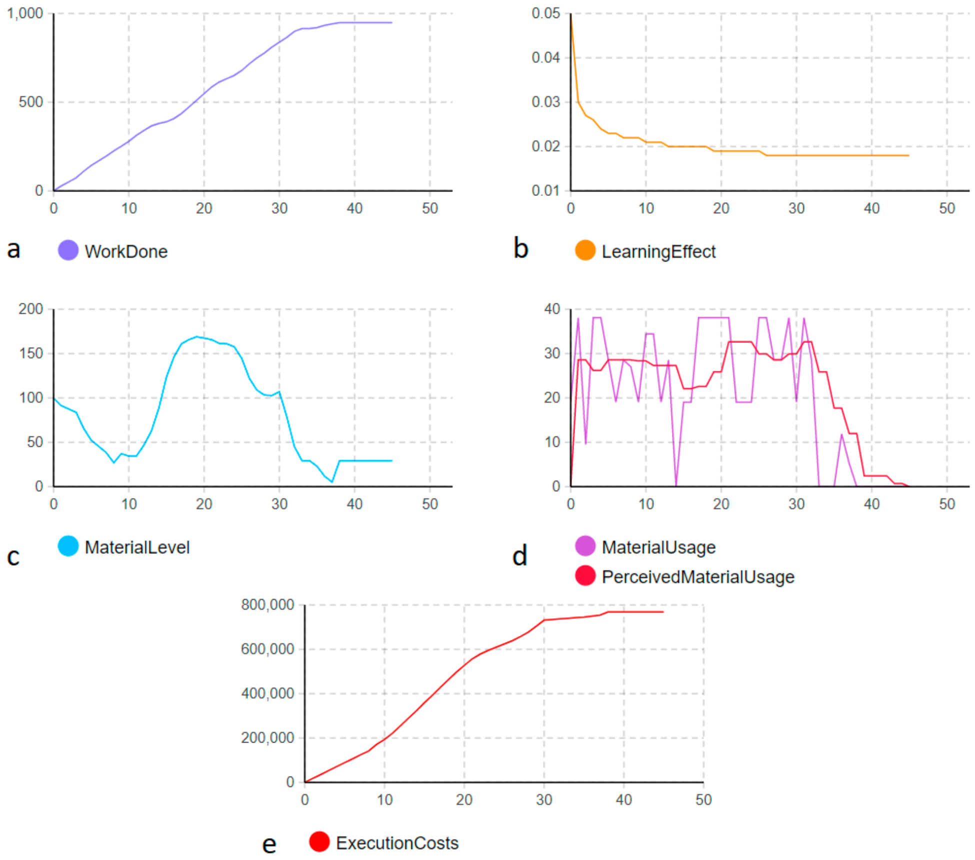

Fig. 8. Selected graphs of the system model's behavior over time: a) Work done (WorkDone) increases up to 948 m^2 of the surface, expressed in square meters; b) Learning effect (LearningEffect) in the process of improving workmanship; c) Material level (MaterialLevel) over the course of the work, expressed as square meters of material in storage; d) Comparison of material usage (MaterialUsage) and perceived material usage (PerceivedMaterialUsage) over time, expressed as square meters; e) Execution costs (ExecutionCosts)

Ryc. 8. Wybrane wykresy zachowania modelu systemu analizowanej roboty budowlanej w czasie: a) roboty wykonane (WorkDone) narastająco do wartości 948 m^2 nawierzchni, b) efekt uczenia się (LearningEffect) w procesie zapewnienia jakości wykonywanych prac, c) poziom zapasów (MaterialLevel) w cyklu realizacji prac, d) zestawienie różnicy między faktycznym (MaterialUsage) i subiektywnym zużyciem materiałów (PerceivedMaterialUsage) w czasie, e) koszty wykonania (ExecutionCosts)

Discussion

The proposed model was presented on a single work, that of the renovation of a wearing course in the historic environment of Wawel Castle's Outer Courtyard. While the work presented may be seen as relatively simple in the context of entire conservation projects that consist of multiple works and face numerous risks to project execution time and cost, such as coming upon unexpected archaeological findings, the simplicity of the work was necessitated to properly and clearly present the model. The model itself can be used to simulate more extensive and complicated works that target historic buildings or entire complexes, and various types of conservation-related risks were explored by the authors on the example of the same project, but using a static, network-based model whose main objective was to investigate the impact of risk on conservation project execution time and cost [Śladowski et al. 2024] and aid in selecting the most optimal project resilience strategy. Network-based models can also be used in adaptive reuse projects that target historic buildings. One such model was proposed for selecting the most optimal set of forms of use for the buildings and defensive structures of the Boyen Fortress in Giżycko, Poland [Śladowski et al. 2021], which also considered adaptability ratings of each building. The key contribution of the approach presented in this paper is that it is dynamic, which allows for the observation of the project system's behavior as the project's execution progresses and any possible risk-related events unfold and impact the project. Presenting it on a simple work was therefore better suited to illustrating how the approach operates, as more complex works would have been unsuitable due to an excessive number of factors that need consideration, but that nevertheless can be modelled using the proposed approach. The work presented also has characteristic features of a conservation project, namely:

- it was executed at a site that was in continued operation throughout the project;
- there was very limited space for storage and craft stations because of the historic environment, which complicated deliveries and material stock management;

- original materials and elements (stone tiles) were reused and to the highest possible degree—a practice common during and specific to conservation projects.

All of these circumstances were modelled using our approach, which makes it suitable for modelling other, more complicated works and sets of works.

Conclusions

The effective estimation of a given construction work's execution time and costs necessitates an analysis of essential, dynamic and typically non-linear relationships between its elements (people, materials, equipment, etc.). Due to the fact that construction works are usually open-ended systems, investigating the interactions of their elements with the external environment is also essential. For the purposes of this analysis, the authors developed a simulation model based on System Dynamics. The proposed model considers typical risk factors which determine the productivity of construction crews such as worker absence due to sick leave, construction equipment failure, material availability problems and ensuring proper workmanship quality, or the impact of poor weather conditions. The presented case of the application of the System-Dynamics–based model proposed confirmed its applicative potential. It should be noted that the model proposed is general in nature, which means it can be used universally to assess the time of construction work execution and can be enhanced and adapted to a specific case, including its risk exposure or atypical conditions. Confirming this requires further testing on other cases of construction works.

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Abstract

This paper presents an approach to modelling and analyzing simulations of construction works using System Dynamics. The authors, using systems thinking, developed a general model of a construction work's performance to assess its execution time and costs. The proposed model considers dynamic and non-linear relations between the elements (people, materials, machines, etc.) of the construction work as a system and its reactions to essential risk factors. The potential of the proposed approach was presented on the example of the construction of a stone tile wearing course for a shared space at the Wawel Royal Castle in Cracow. The authors wish to note the universality of the model, whose general form can be used to assess the execution times and costs of typical construction works that are vulnerable to essential risk factors.

Streszczenie

Przedstawiono podejście do modelowania i analizy symulacyjnej robót budowlanych oparte na dynamice systemów. Korzystając z myślenia systemowego, opracowano ogólny model roboty budowlanej na potrzeby szacowania cyklu jej realizacji. Zaproponowany model uwzględnia dynamiczne i nieliniowe relacje pomiędzy poszczególnymi elementami (ludzie, materiały, maszyny itd.) roboty budowlanej oraz jej interakcje z podstawowymi czynnikami ryzyka. Możliwości zaproponowanego podejścia zaprezentowano na przykładzie roboty budowlanej: wykonanie warstwy ścieralnej z nawierzchni z płyt kamiennych ciągu pieszo-jezdnego zlokalizowanego na terenie Zamku Królewskiego na Wawelu w Krakowie. Zwraca się uwagę na uniwersalny charakter opracowanego modelu, którego ogólna postać może stanowić bazę do szacowania cyklu realizacji typowych robót budowlanych podatnych na wpływ podstawowych czynników ryzyka.