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Research paper

Synchronizing production of precast elements with on-site erection

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Abstract: Offsite construction technologies are developed to reduce project cost and duration. To make the most of the potential offered by prefabrication the planner should consider the whole supply chain. A failure to coordinate the off-site production with on-site erection is a source of waste (waiting time of the construction crews or redundant handling activities on-site). Most of the research to date focused on optimizing operations of a prefabrication plant assuming a deterministic schedule of demand for its products. The purpose of this paper is to develop a mathematical model for integrated scheduling of offsite and on-site operations. Its solution is a schedule that minimizes the downtime of both the prefabrication plant and the on-site erection crews. In accordance with the Just-in-Time concept, the prefabrication schedule is set in a way to reduce the stocks of finished products, thus reducing the storage area and cost of funds tied up in inventory. The schedule's robustness against the disturbance in the production and erection workflows is assumed to be assured allocating time buffers. The advantage of the proposed method is the ease of collecting the input: instead of detailed cost records, estimates of unit cost of lost time can be used.

Keywords: precast concrete, construction project scheduling, production plan optimization, mathematical modeling

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1. Introduction

Prefabricated construction involves the on-site assembly of components fabricated at permanent, temporary, or mobile manufacturing facilities. The advantages of using prefabrication in construction are numerous, and they are usually considered in the broad category of reduced building life cycle costs [1, 2]. Transferring the most labor-intensive primary production processes to the controlled environment of a production plant promotes quality, offers economies of mechanization (automation, robotization), and makes the course of production process execution independent of the weather. In particular, building of precast concrete elements is claimed to improve the construction safety, reduce energy consumption and pollution of the environment [3]. Compared with standard on-site methods of forming concrete elements, a precast concrete production plant makes better use of machine work and offers a broader choice of concrete compacting and curing methods to the benefit of the elements' strength and aesthetics. Cements with high early and standard strength, additives and admixtures that accelerate maturation, and heat treatment (e.g. low-pressure steaming) can be used with much greater control of the development of their properties in the element being formed. Elements' connections are commonly designed for quick assembly so that the frame can be loaded immediately. Therefore, non-structural works can start as soon as the structure of a section of a building is completed. This way, finishing works partly overlap with assembly of the frame, which helps compress the schedule.

The selection of precast elements' size, complexity, and the level of pre-finishing largely depends on the capabilities of the means of transport and lifting equipment. Transport and lifting operations have a significant impact on the prefabricated construction. The on-site cranes tend to be the assembly process' bottlenecks; unification of the precast elements' dimensions and weights helps make a full use of their capacities. If very large elements are to be used, on-site pre-assembly of smaller, easy-to-handle sub-components may reduce transport costs. The dimensional or modular standardization of prefabricated elements helps the precast plant optimize production processes, so increase production and reduce costs [4].

Labor- and cost-intensive handling operations and the need to stock elements at the construction site can be eliminated by synchronizing deliveries with the assembly process. Further cost reduction can be achieved by synchronizing the on-site assembly operations with the production of the precast elements. From the supplier's perspective, reduced inventory space, lower working capital requirements, and better utilization of production potential are just some of the benefits of synchronizing processes within the supply chain.

Since the late ninety-fifties, so the advent of precast concrete, the uptake of this new technology has differed country to country. In Poland, prefabrication dominated the multi-family housing market in 1965–1985. It then declined rapidly with the transition from a centrally controlled economy (end of mass housing projects) and a growing aversion to uniformity in housing architecture. The fact that the technology was not mature enough and the quality of both elements and erection workmanship was considered low did not help the survival of the prefabrication industry in this difficult period. Hower, already in the late nineteen-nineties, precast concrete began to return to favor, first in the sector of industrial buildings. Studies on the performance of the old prefab housing stock contradicted the popular opinion in its inferiority and indicated that, with proper maintenance and some modernization, it can safely serve for decades [5]. Architects and manufacturers of building materials announce a great comeback of prefabrication in Polish residential architecture [6]. This trend is observable worldwide: the technology evolves to answer the growing demand for efficiency, quality, and sustainability, often in the context of passive construction, with certified components appearing on the market [7].

Today, CAD/BIM software is increasingly used to support design and manufacturing. Computer modeling helps eliminate design errors, accelerates the design process, and improves design consistency. It also provides complete information for manufacturing and assembly teams.

2. Just-in-time paradigm and the construction industry

On the one hand, transferring labor-intensive processes from the construction site to the prefabrication plant may reduce construction time risks due to the reduced impact of the weather on the erection processes. On the other hand, each link in the supply chain is a source of specific risks: disruption in the prefabrication process is likely to propagate on the construction site. Untimely deliveries destroy construction schedules, are the source of non-value-adding material handling operations, and increase inventory costs [8]. Such a supply chain functions regardless of whether it is managed in an integrated or dispersed manner [9]. However, integrated management of the supply chain (in this case, synchronizing prefabrication with on-site erection) helps reduce waste: downtime for both fabrication plants and on-site crews and the cost of funds tied up in the inventory.

According to a study by Ghosh and Hamad [10], the time lag between the start of prefabrication and the start of assembly, as well as the pace of production (conditioned by the capacity of the prefabrication plant), have a significant impact on the time and cost risk. Elements coming off the production line often require some time in the yard to complete the curing process, then are transported to the construction site, unloaded into a yard or, preferably, erected directly from the means of transport. The pace of production, batch size, and delivery schedule depend on the progress of the assembly process. The primary and secondary production processes run concurrently and should be planned on an equal basis.

Traditionally, the Critical Path Method (CPM) has been used to plan the execution of assembly work by calculating the earliest and latest start and completion dates of subsequent assembly stages. The delivery schedule assumes that prefabricated components should be available on site at the earliest dates to avoid delays in the start of assembly of subsequent prefabricated components. This assumption may result in increased inventory (i.e., increased storage costs and freezing of the contractor's working capital) to ensure continued on-site operations even if deliveries are delayed. On the other hand, letting the element production start later than on the CPM's earliest start may lead to missing the project due dates if the on-site works do not progress exactly as planned.

Several models that integrate primary production at the construction site and secondary production at precast plants have been presented in the literature. Li et al. [11] developed a precast production planning model to minimize the total production cost while meeting the demand at the construction site. The model was solved using genetic algorithms and branch-and-bound methods. Benjaoran and Dawood [12] presented a system that uses artificial intelligence algorithms, including genetic algorithm and artificial neural networks, to support the planning of prefabrication plants. The system aims to reduce customer lead time and optimize resource utilization in the factory. Wang et al. [13] proposed a precast production planning model based on multi-agent systems to synchronize the production schedule and resource allocation of precast components. All of these approaches are based on deterministic schedules of demand for precast components and do not consider inventory costs.

Dan and Liu [14] constructed an integrated model for scheduling of production and transportation precast elements with delivery time windows. Their objective function minimizes all of the following: in-plant early cost, the total penalty cost of delivery, and transportation cost. Genetic algorithm was employed to find the solution.

Ko [15] proposed a framework for reducing finished product inventory levels. Fuzzy logic was utilized to calculate time buffers that safeguard the prefabrication plant against capacity losses due to demand variability. Demand fluctuations may arise from various factors, such as delays in on-site erection processes and design changes during construction. Additionally, the framework allows for the reduction of product inventory by delaying production start dates, specifically the latest dates with buffers. Anvari et al. [16] considered combined manufacturing, transportation, and assembly problem with the goal of minimizing time and cost of prefabrication. However, they did not consider construction costs or losses associated with interruptions in the on-site operations. To solve this problem, they developed a multi-objective Genetic Algorithm-based searching technique.

Just-in-Time (JIT) scheduling can reduce inventories of precast elements, both on-site and at the factory, and thus lower logistics costs. This method is particularly suitable for congested building sites in densely populated cities where storage areas are unavailable. The approach relies on timely deliveries of materials in the required quantity and quality. JIT is based on synchronizing production processes at the prefabrication plant with the progress of the erection operations, and assuring that the materials reach the construction site exactly when needed, in right quantities and with right quality [17].

The JIT philosophy originates from Japan automobile industry. Its concept implies an uninterrupted flow of work between successive elements of the production chain. In order to reduce costs, it is necessary to eliminate waste and all non-value-adding activities. This includes the elimination of inventory and production downtime – materials must be delivered on time, as required. So the flow of materials is pulled by the demand side (Kanban or pulled system) [18]. Of course, production operations can be carried out if the delivered materials are of sufficient quality, so it is necessary to support by the Total Quality Control concept. Further improvement of the achieved results can be achieved by enhancing relations with suppliers and optimizing the execution of value-adding activities [19].

With JIT used in precast construction, the production of elements begins as late as possible to ensure uninterrupted flow of processes carried out at the construction site. This reduces the size of inventories at both the plant and on-site. The pull-off system inventory management, also known as the auxiliary production system, is vulnerable to disruptions. Delays in the production process can propagate to on-site operations, resulting in downtime of on-site resources, delays, missed deadlines, and contractual penalties for the contractor. Therefore, some buffer inventory is to be maintain to compensate disturbance in production as well as on site [4]. This may discourage contractors from implementing this method in practice. However, with careful planning, these risks can be overcome.

Low and Choong [20] surveyed engineers supervising 32 precast projects in Singapore. Analysis of the survey results identified the key difficulties in implementing JIT. These included: insufficiently detailed or inaccurate delivery schedules, delays in updating these schedules in the event of disruptions, and the occurrence of emergency situations requiring emergency deliveries. Fristia and Adi [21] conducted a survey on barriers to implementing JIT in construction in Indonesia. Respondents confirmed that a facilitating factor in implementing JIT on construction sites is the simplification of work processes, particularly through the use of prefabricated building components.

If the contractor selects the precast element supplier based solely on the lowest price [22], there is a risk of underestimating the logistics cost. The suppliers may be more competent in arranging the logistics of Just-in-Time deliveries. Therefore, it is expected that tightening the cooperation between the supply chain members will reduce logistics costs throughout the supply chain, and the resulting economies may motivate the suppliers to offer JIT deliveries.

There are two interrelated decision problems that the prefabricator's technologists and production engineers must solve. The first is to control material and product inventory levels; the other is production scheduling. This issue becomes complex when certain prefabrication molds serve only specific products, and the products must be made in a predetermined sequence to meet delivery dates agreed with the clients.

Kong et al. [23] confirmed the effectiveness of Just-in-Time strategies in managing the supply chain of prefabricated construction products. The proposed model minimizes delay penalties, on-site assembly waiting costs, and environmental emission penalties (i.e. earliness/tardiness costs). Xie et al. [24] also proposed a production planning model in accordance with the JIT concept for the production of prefabricated steel box girders used in bridge construction. The optimization also targeted earliness and tardiness costs, assuming that the demand dates for components are known and fixed.

Tan et al. [25] simulated logistic processes for a light rail transit (LRT) project in Singapore. They found that adopting a pull-driven scheduling approach can result in reducing inventories to be kept by the prefabrication plant. According to Chen et al. [26], considering a weighted combination of manufacturing and installation costs as the goal of the scheduling of on-site and off-site operations in prefabrication would be beneficial from the point of the general contractor.

This paper presents a mathematical model for synchronizing primary production (on-site erection) and auxiliary production (element precasting). Unlike the methods presented in the literature, the proposed approach assumes that the erection schedule is not predefined. Instead, it is determined by solving the optimization model. The production start dates for precast elements are synchronized with the days they are to be used by the contractor to minimize downtime at the precast plant and at the construction site. This approach is based on the Just-in-Time concept. To account for potential disruptions to both in-plant and on-site production proposed model includes buffers in the schedule.

3. The model for synchronizing prefabrication and assembly operations

Erecting the prefabricated frame usually coincides with other construction activities to complete the building structure. The schedule of erection is determined by the progress of other processes within the project's scope. Let us assume that the project, encompassing both the on-site and offsite (prefabrication) processes, is modeled as an activity-on-node network. Let $A = \{1, 2, \ldots, n\}$ represent the set of processes, and $G = \langle A, E \rangle$, $E \subset A \times A$ represent the directed graph of precedence relationships. The durations t_i of processes $i \in A$ are deterministic. The unknowns are the start and finish dates of each process, denoted by s_i and $f_i = s_i + t_i$, respectively, to be calculated under the assumption that the project completion time cannot exceed T, and prefabrication processes may commence before on-site works.

The precedence relationships between processes (represented as network arcs) $(u, v) \in E$ are of finish-to-start type. If necessary, time lags $\Delta_{u,v}$ can be introduced to capture the amount of delay between the starts of a process v and its predecessor u. The precedence relationships results from the logic of works conditioned by the construction methods and available resources.

Let C represent the set of resources (construction crews and the prefabrication plant, the latter depicted by $p \in C$). The set of processes conducted by the prefabrication plant is A^p. Another distinct member of the set of resources is the erection crew $m \in C$. As each resource can execute only one process at a time, then each resource $c \in C$ can be assigned a sequence of processes $(a_k^c)_{k \in A^c} = (a_1^c, a_2^c, \ldots, a_k^c, \ldots, a_l^c)$, where $A^c$is a set of processes entrusted to resource $c \in C$, a_1^c is the process to be executed as the first, and a_l^c as the last. Sequential execution means that a process cannot start until the previous process has finished, $s_{a_{k+1}^c} \geq f_{a_k^c}$.

In the set of all processes related with the analyzed project, $A = \{1, 2, \ldots, n\}$, a specific subset comprises precast elements at the prefabrication plant and erecting these precast elements on site. Let B be a set of process pairs (r, s) , where the former is precasting, and the latter on-site erection of elements, $r \in A^p,\ s \in A^m$. Precasting must start early enough so that the elements are delivered as needed on-site. The precasting lead time in relation to erection is δ. The lead time results from the time required for production and curing until the elements are ready for transport.

Similarly, there is a lead time τ between the completion of on-site erection process and the completion of production of the elements to be erected. It serves as a buffer protecting the schedule against delays caused by untimely supplies attributable to random disturbance in production and transport. The greater τ, the greater the inventory of elements kept in the prefabrication plant or at the construction site. Inventory generates cost. Let w_b represent the cost of keeping stocks of one day production of precast elements (including the cost of tied-up capital), w_p be the cost of one day idle time of the prefabrication plant, and w_m the – the cost of one day of idle time of the on-site erection crew.

The proposed model is intended to schedule processes in a way that minimizes costs that are attributable to unsynchronized work and overstocking. Therefore, the objective function of the mathematical problem model is as follows:

$$\min z : z = \sum_{(r,s)\in B} w_b \cdot (f_s - f_r - \tau) + w_p \cdot \left(f_{a_k^p} - s_{a_1^p} - \sum_{k\in A^p} t_k\right) + w_m \cdot \left(f_{a_k^m} - s_{a_1^m} - \sum_{k\in A^m} t_k\right). \tag{3.1}$$

The first process starts at 0 (the beginning of the first day of construction). The date of completion of all processes on site must not exceed the predefined due date T (as agreed in the contract). Therefore:

$$s_1 = 0, \tag{3.2}$$

$$f_n - s_i \le T, \qquad \forall i \in A \setminus A^p. \tag{3.3}$$

As each process is assumed to run continuously, the time for its completion f_i is:

$$f_i = s_i + t_i, \qquad \forall i \in A. \tag{3.4}$$

The process start dates s_v are determined by precedence relations defined in the project network model, so:

$$s_v \ge f_u + \Delta_{u,v}, \qquad \forall (u,v) \in E. \tag{3.5}$$

Prefabrication of elements needed for a particular erection process should begin in advance of the planned start of this process, therefore:

$$s_s \ge s_r + \delta, \qquad \forall (r,s) \in B. \tag{3.6}$$

Prefabrication of elements needed for a particular erection process should be completed in advance of the planned completion of the erection on site:

$$f_s \ge f_r + \tau, \qquad \forall (r,s) \in B. \tag{3.7}$$

A boundary condition assures that no processes begins before the start of the project:

$$s_i \ge 0, \qquad \forall i \in A. \tag{3.8}$$

All conditions and constrains (Eq. (3.2)–(3.8)) as well as the objective function (Eq. (3.1)) are linear. Therefore, the model can be solved using a standard solver.

4. Example

The application of the model is presented using a notional case of a project to erect the superstructure of a pair of non-identical buildings (for simplicity, the network model excludes substructure, roofing, and non-structural works). The structural masonry walls of both buildings are made of ceramic blocks, while the floors are of hollowcore slabs. The precast slabs are delivered from a factory located near the construction site.

Masonry processes are labeled as "w_no. of building_no. of story" (e.g. w_1_2), placing hollowcore slabs as "s_no. of building_no. of story" (e.g. s_2_3). The production process of each hollowcore slabs is also identified by the number of the story and the number of the building being its destination, as "p_no. of building_no. of story" (np. p_1_1). The network model is presented in Fig. 1.

In the network model, no relationships between the hollowcore production and erection are marked as these are defined by relationships defined by Eq. (3.6) and Eq. (3.7). Table 1 summarizes input for calculations, so the list of processes and their durations expressed in working days.

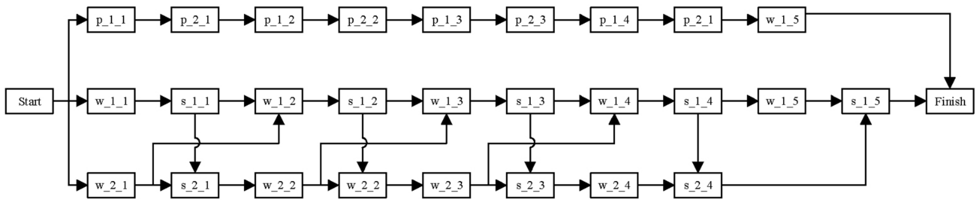

Fig. 1. Project network (example)

Table 1. Project data (input for the case analysis)

Building number	Story number	Masonry wall erection time [days]	Hollowcore slab assembly time [days]	Hollowcore production time [days]
1	1	12	5	8
	2	10	5	8
	3	10	5	8
	4	10	5	8
	5	8	4	7
2	1	8	4	7
	2	8	4	7
	3	8	4	7
	4	6	3	6

The project's completion time cannot exceed 100 days. The masonry walls are delivered by one crew of masons, and the sequence of their works is as follows: they start with the first story of Building 1, then move to Building 2. As the floor slabs above the first story of Building 1 and the walls of the first story of Building 2 are completed, the masons return to Building 1 to erect walls of the second story, and continue in the same manner until the masonry works are completed.

Similarly, there is one crew to install hollowcore slabs who move from building to building. As the joints between the precast elements need to be filled with concrete and cast-in-place tie beams are needed to complete the structure, a 3 day waiting time is scheduled between the completion of the slab and the start of masonry walls on its surface for the concrete to reach sufficient strength.

According to interviews with experts (construction managers and prefabrication plant managers), the cost of one day of idle time of an erection crew is twice the cost of a day of stockpiling precast elements, and three times less than the unit cost of the prefabrication plant's idle time.

It is recommended that hollowcore slab production begins at least three days before they are to be installed on site, and should end four days before installation on site is completed. These lead times are technology-related: to leave enough time for production and curing in the factory, and risk-related: to allow for disturbance in production and transport.

The mathematical model of the case was solved using Lingo 14.0. With the proportion between the unit (per day) cost of precast elements' warehousing, the idle time of the prefabrication plant, and the idle time of the erection crew as described above (respectively, $w_b = 1$, $w_p = 6$, $w_m = 2$), the optimal solution has a duration of 86 days.

The changes in unit costs have no impact on this duration. As the unit costs are not expressed as absolute, but as relative values, they can be treated as criteria weights for minimizing, respectively, the warehousing cost, plant idle time and erection crew idle time.

Hollowcore slab production for the project starts five days after commencement with works on site, and is completed after 74 days. The total idle time of the prefabrication plant is 3 days. Precast elements are stored 24 days longer than the assumed time buffer.

The total idle time of the erection crew is 35, and this value is not affected by the weights, so the proportions between the unit costs of warehousing, plant idle time, and erection crew idle time. The erection crew's idle time is the result of the lack of synchronization between the labor-intensive masonry works and quick installation of the slabs. To make a better use of this resource, the assembly crew could be regularly transferred to another construction site (if practical), or assist the masons with their tasks.

A sensitivity analysis was performed to check how the optimal solution reacts to modification of the model weights. The solution was not sensitive to changes of w_m. The same solution was obtained at $w_b \in \langle 0.86, 1.19 \rangle$ (decrease by 14% and increase by 19%) and at $w_p \in \langle 5.01, 7.00 \rangle$ (decrease by 16.5% and increase by 16.7%). It is important to know these ranges to accurately estimate the unit costs since they are not shown separately in the company's accounts.

The model was further analyzed to check the possibility of reducing precast elements' warehousing time and minimizing plant downtime. Continuous plant operation was achieved at $w_p = 7.01$, but the warehousing time grew substantially to 45 days.

Elimination of warehousing was possible at $w_b = 6.00$, but at a cost of increasing the prefabrication plant's idle time to 11 days. In both cases, the value of the objective function is greater than in the solution obtained for the original set of weight values.

5. Conclusions

With the development of mechanization, robotics and concrete technologies, precast manufacturers introduce elements and systems with excellent strength and aesthetic parameters. They also implement new production management systems to improve productivity, optimize time management, and enhance the quality of their product. One modern management concept being implemented in the industry is Lean Management. Its aim is to continuously optimize costs while improving product quality levels, shortening production processes, managing warehouses, and eliminating waste. To achieve these effects, well-known supporting methods are used, including Just-in-Time, the advantages of which are discussed in the article, Total Quality Management, Reengineering, and others. However, the best results from the application of these methods can be achieved by applying them to the management of the whole construction supply chain and considering all its participants as a single organization. In this approach, integrated planning of all supply chain processes is important. In the case of prefabricated construction, not only streamlining prefabrication processes, but also ensuring the synchronization of production with the progress of work in the construction site have a major impact on reducing construction costs. The purpose of synchronization is to reduce unproductive time – idle time of production facilities and on-site resources, and reduce inventories.

Achieving the best synchronization effects is not possible with the traditional approach in construction production scheduling, based on the use of the CPM method. This method assumes the full availability of all resources required for construction production. In addition, it is traditionally used to determine the amount of material and prefabricated elements required, resulting from the optimal execution of construction processes, which ensures that the project duration is minimized. However, it does not allow for the integrated planning of execution times for construction processes and the supply of materials and prefabricated elements.

The paper presented a method of planning prefabrication together with erection processes to minimize costs associated with idle time and excessive inventory. The proposed model has the advantage of being based solely on the estimates of proportion between unit costs of time losses, with no need to extract precise cost data from cost records. The linear form of the model makes it easy to obtain optimal solutions by means of standard solvers.

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Synchronizacja produkcji prefabrykatów z realizacją procesów podstawowej produkcji budowlanej

Słowa kluczowe: montaż konstrukcji prefabrykowanych, harmonogramowanie przedsięwzięć budowlanych, optymalizacja planu produkcji, modelowanie matematyczne

Streszczenie:

Zintegrowane zarządzanie łańcuchem dostaw oraz zapewnienie synchronizacji produkcji prefabrykatów z montażem na budowie może przynieść efekty w postaci redukcji przestojów zarówno wytwórni jak i brygad roboczych, zmniejszenia kosztów magazynowania prefabrykatów oraz zamrożenia środków finansowych w zapasach. Duży wpływ na ryzyko czasu i kosztu ma termin rozpoczęcia procesu prefabrykacji w stosunku do terminu rozpoczęcia montażu oraz tempo produkcji, zależne od mocy produkcyjnej zakładu prefabrykacji. Tempo produkcji i wielkość partii oraz terminarz dostaw są uzależnione od postępu procesu montażu – procesy produkcji podstawowej i pomocniczej przebiegają równocześnie i powinny być planowane równorzędnie. Celem synchronizacji jest redukcja kosztownych strat czasu – przestojów w pracy wytwórni i prac na budowie, ale również zbędnych zapasów elementów. Terminy montażu elementów są zatem uwarunkowane przebiegiem realizacji innych procesów w ramach danego przedsięwzięcia. W artykule zaproponowana model matematyczny problemu synchronizacji produkcji podstawowej i pomocniczej realizowanej w wytwórni prefabrykatów. W odróżnieniu od wcześniej przedstawionych w literaturze metod, proponowane podejście zakłada, że terminy montażu elementów nie są sztywne, lecz są ustalane poprzez rozwiązanie opracowanego modelu optymalizacyjnego. Terminy rozpoczęcia produkcji poszczególnych partii prefabrykatów są synchronizowane z terminami zapotrzebowania w celu redukcji przestojów pracy wytwórni oraz brygad realizujących poszczególne procesy budowlane. Podejście to bazuje na koncepcji metody JIT, lecz uwzględnia możliwość wystąpienia zakłóceń zarówno w produkcji w zakładzie jak i na budowie poprzez uwzględnienie w harmonogramie buforów czasu. W artykule zilustrowano zastosowanie proponowanego modelu na przykładzie realizacji przedsięwzięcia polegającego na realizacji kompleksu dwóch budynków w stanie surowym o konstrukcji mieszanej. Przeprowadzono analizę wrażliwości uzyskanego rozwiązania na zmiany wag modelu (kosztu jednego dnia przerwy w pracy brygady montażowej, kosztu dziennego gromadzenia zapasu elementów i jednostkowego kosztu przestoju wytwórni). Utworzony model poddano także analizie pod kątem możliwości i skutków eliminacji zbędnego czasu składowania prefabrykatów oraz przestojów w pracy wytwórni. Przykład został rozwiązany z wykorzystaniem Lingo 14.0. Zaproponowany w artykule podejście pozwala zaplanować terminy produkcji prefabrykatów oraz dostosować do nich terminy prac montażowych w celu minimalizacji kosztów związanych z przestojami i gromadzeniem nadmiernych zapasów. Zaletą opracowanego modelu matematycznego jest możliwość bazowania jedynie na oszacowaniu wzajemnych relacji pomiędzy kosztami jednostkowymi strat czasu, bez konieczności dostępu do szczegółowych danych z ewidencji kosztów. Zaproponowana postać liniowa modelu pozwala na zastosowanie do jego rozwiązania dostępnych powszechnie solverów.

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