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SCHEDULING REPETITIVE CONSTRUCTION PROJECTS: STRUCTURED LITERATURE REVIEW

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Abstract. Construction projects that involve repetitive operations are often referred to as repetitive construction projects. Scheduling them proves a task more demanding than in the case of projects in other industries. Typical objectives of optimization, a characteristic set of constraints, as well as the schedule's susceptibility to the propagation of disruptions caused by materializing risks, call for specific scheduling methods. The authors review the literature to summarize the existing repetitive scheduling methods and put forward their classification to identify the method's aspects needing refinement. This is done to point to directions of further research. The authors hope that this study will contribute to better identification of existing problems in planning repetitive construction projects and faster development of decision support systems, eagerly anticipated by the construction practitioners. Though the focus is on applications to construction projects, the repetitive scheduling methods that account for volatile operating conditions may be of interest to researchers who develop planning techniques for other industries.

Keywords: construction project management, construction project planning, construction project scheduling, project management, project schedules, repetitive construction projects.

Introduction

The specific nature of construction projects makes them more challenging than most projects in other business areas (Jaśkowski & Biruk, 2018; Tomczak, 2019). The factors that make planning repetitive construction projects difficult are:

- a considerable impact of the weather on the course of works carried out in open space and high costs of technical measures to reduce the adverse impact of the weather;
- an individual character of each project (construction of two buildings of identical design, but in a different time of year or located in different geographical or hydrological conditions may require the use of different methods and organization);
- the immobility of the products of construction, which means that materials, machinery, the crews together with safety and health protections must be constantly moved around the construction site (in contrast to an industrial plant, where a workpiece is moved to successive fixed work stations);
- the size and weight of the products of construction (they consume large quantities of material resources that need to be brought to the construction site, which requires careful planning and generates considerable cost);
- long production cycle – late effects resulting from the construction of facilities and late financial settlement of the construction;
- the necessity to create a smoothly working organization out of a large number of people from different companies, with different education, skills, and experience;
- high costs of consequences of wrong decisions made both at the stage of planning and execution.

A particular category of construction projects is repetitive construction projects, such as roads, high-rise buildings, or estates of single- or multi-family buildings. Their scope is usually divided into units, where specialized crews of fixed composition conduct the same type of work, passing from one unit to the other. Construction processes are usually scheduled to be performed continuously and at a steady rate. This way, the organization of works resembles a well-synchronized production line, with different processes running concurrently in different units. How-

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*Corresponding author. E-mail: *m.tomczak@pollub.pl* ever, even small fluctuations in the productivity of crews, very likely in the volatile environment of the construction site, generate disturbance in the flow of work and significant inefficiencies. Therefore, the traditional construction scheduling methods, such as the Critical Path Method, Precedence Programming Method, and Program Evaluation and Review Technique, are not suitable for planning repetitive construction projects (Arditi et al., 2002a; Bakry et al., 2016; Su & Lucko, 2016).

Many methods dedicated to repetitive scheduling have been developed over the years. Though the body of literature on the subject is considerable, the authors of this paper found no publication that summarizes and compares the numerous approaches and techniques. This paper is an attempt to bridge this gap by collecting and presenting the methods for planning repetitive construction projects. To systematize the existing knowledge on the subject, the authors put forward a classification of methods, indicate their aspects that need refinement, and conclude with a list of potential directions of further research.

The paper is structured as follows: Section 1 is devoted to defining repetitive projects and providing their systematics as seen by different sources to specify the focus of the analysis. Section 2 is the actual literature review. Subsection 2.1 presents its methodology. Subsection 2.2 describes the material collection process. Subsection 2.3 is the quantitative analysis of publications. Subsection 2.4 proposes a systematics of the publications, analyses and evaluates them. Section 3 presents a summary of the review. Section 4 is a discussion on the findings of the literature study in attempt to identify shortcomings of the existing repetitive scheduling methods and to predict directions of their further development. Final section presents the conclusions.

1. Repetitive construction projects: definitions and classifications

Projects involving repetitive processes are often referred to as repetitive projects. This misleading notion does not result from the repetitive character of the project as a whole, as the projects are unique by nature. However, the material scope of some projects can be broken down into a number of elements whose delivery consists in the same type of work. This way, the execution of a project involves repeating some activities (construction processes or works) in different units (locations). A project's scope may consist of both repetitive and unique units. A unit is thus a distinct part of a repetitive construction project.

Typically, the planner's aim is that the same resources (specialized construction crews of fixed composition) carry out construction processes in subsequent units. The next process in a unit may start after its predecessor is completed, and the crew has finished its work and moved to the next unit. Frequently, the processes in each unit are scheduled in a fixed order. Each process is expected to run continuously (i.e., the crews move from unit to unit without waiting), and at a steady rate. Dividing the project into units to synchronize processes, and entrusting the same work to the same people is expected to reduce project duration and produce economies by both eliminating idle time and increasing productivity by specialization (learning effect). However, scheduling such projects is a challenging task. Differences in the productivity of individual teams and differences in the pace of implementation of individual processes accumulate when they are repeated on all work sections leading to inefficiency and breaks in the work of crews.

One of the most frequently cited classifications of repetitive construction projects is the one presented by Hegazy et al. (2014), who prompt three basic categories of such projects:

- linear horizontal, e.g., construction of roads, pipelines, and tunnels;
- non-linear vertical, e.g., construction of a tall building;
- non-linear scattered, e.g., construction of a group of detached houses, renovation of a bridge.

Another classification was proposed by Murguia and Urbina (2018). They distinguish three following classes of projects: repetitive linear, repetitive non-linear, and non-repetitive. Table 1 summarizes their key features.

Ioannou and Yang (2016) divided the repetitive projects first according to the physical shape of the structure under construction into discrete (vertical) and continuous (horizontal or linear), and second, according to the scales adopted to measure the progress of works – into the uniform (counting scale) and nonuniform (dominant-attribute scale).

A number of works (Ammar & Abdel-Maged, 2018; El-Rayes & Moselhi, 1998; Tomar & Bansal, 2020; Zou & Zhang, 2020) divide repetitive projects into the following two groups:

- typical projects – where there is the same amount of work related to a process in each unit, and the processes in each unit consume the same quantities of non-renewable resources in each unit;
- non-typical or atypical projects – where the units differ in the amount of work and resource requirements.

Hassan and El-Rayes (2020) divide repetitive projects into two classes, focusing on the nature of relationships between activities intended for a unit:

Table 1. Classification, proposed by Murguia and Urbina (2018)

Project	Size of units	Operations per unit	Resources per unit	Flow	Outputs per location
Repetitive Linear	Equal	Equal	Equal	Smooth	Equal
Repetitive Non-linear	Not uniform	Equal	Not uniform	Moderate	Not uniform
Non-repetitive	Unequal	Unequal	Not uniform	Turbulent	Unequal

- serial projects, where a repetitive process has only one predecessor and one successor in each unit;
- non-serial projects, where a repetitive process may have more than one predecessor or successor in a unit.

Other classifications are simplifications of those presented above or combinations of them (Eid et al., 2021; Heravi & Moridi, 2019; Ungureanu et al., 2019).

2. Research method

The method of the literature study was based on procedures applied by de Araújo et al. (2017) and Seuring and Müller (2008). Its four steps are collection of the material, statistical analysis, classification of the material, and evaluation.

2.1. Material collection

The collection of source materials was based on keyword search in two databases, SCOPUS and Web of Science. The query consisted of the following combination of the words "Schedul* AND construction AND repetitive" to be identified in the titles, abstracts, or keywords (TITLE-ABS-KEY). The search was limited to refereed journal papers in English. Books and conference proceedings were excluded. Then the search was continued in papers published in eight major journals from the field of construction project engineering: *Automation in Construction*, *Canadian Journal of Civil Engineering*, *Construction Management and Economics*, *Engineering*, *Construction and Architectural Management*, *International Journal of Construction Management*, *International Journal of Project Management*, *Journal of Civil Engineering and Management*, and *Journal of Construction Engineering and Management*.

As a result, 238 papers potentially related to the topic were identified. A brief analysis of the content helped eliminate 45 as not consistent with the topic, leaving 193 items to be analyzed. The material selection process is presented in Figure 1.

2.2. Statistical analysis

The first step in the statistical analysis of the sample was to determine the distribution of the number of publications over time. The trend (indicated by the dotted line visible in Figure 2) indicates that the topic of scheduling repetitive projects is being addressed more and more frequently.

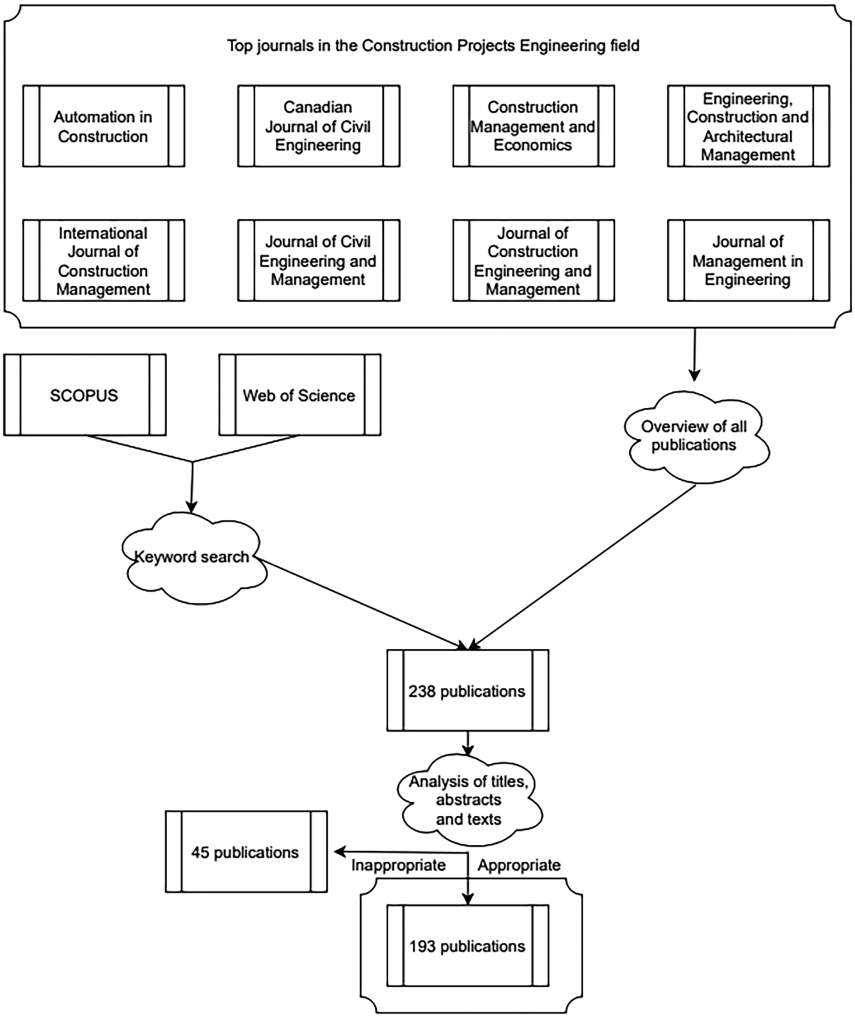

Figure 1. Selection of publications

Since 2001 there is a visible increase in the number of papers on the subject, published every year. The year with the highest number of publications on the subject of scheduling repetitive construction projects is 2020 (15 publications). Figure 2 provides a detailed breakdown of the number of publications by year of publication.

The most productive author in the field of harmonizing processes in repetitive construction projects is Osama Moselhi of Concordia University. He has authored and co-authored 14 articles in this field; according to SCOPUS, his works have been cited 457 times. The next persons in terms of the number of publications are Khaled El-Rayes from the University of Illinois at Urbana-Champaign and Gunnar Lucko from the Catholic University of America with 11 publications. Other authors with significant contributions in this area are David Arditi (Illinois Institute of Technology), Xin Zou (North China Electric Power University), Tarek Hegazy (University of Waterloo), Onur Behzat Tokdemir (Middle East Technical University), and Lihui Zhang (North China Electric Power University). A detailed summary of the number of publications by each author developing the topic of scheduling repetitive construction projects can be found in Figure 3.

Most papers are affiliated to organizations based in the United States of America (66). Another country with significant influence on the development of methods and tools for scheduling repetitive construction projects is Canada with 28 publications. Many publications come from Taiwan, Egypt, China, Poland, and South Korea. The distribution of the number of publications by country is shown in Figure 4.

2.3. Category selection

To systematize the items of the sample according to their focus (i.e., the scheduling objectives), they were divided into the following mutually exclusive categories:

- traditional repetitive project scheduling methods and tools to improve overall workflow;
- resource-oriented scheduling of repetitive construction projects;
- increasing repetitive schedule's reliability and robustness against random disruptions;
- minimizing the duration of repetitive projects;
- minimizing the cost of repetitive projects;
- multi-objective approach to repetitive projects scheduling;
- other.

The allocation of articles to each category is tabulated in Appendix (Table A.1). Most of the authors approached the problem in a comprehensive way and consider multiple constraints and optimization objectives. For this reason, many papers could be attributed to several categories. However, a rule "one paper, one category" was adopted, and the paper assignment process followed the scheduling objective indicated as the main one by the authors and subjective assessment of the authors of this article.

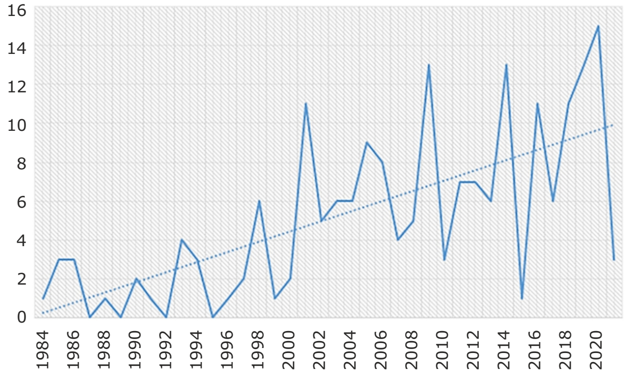

Figure 2. Distribution of publications by year

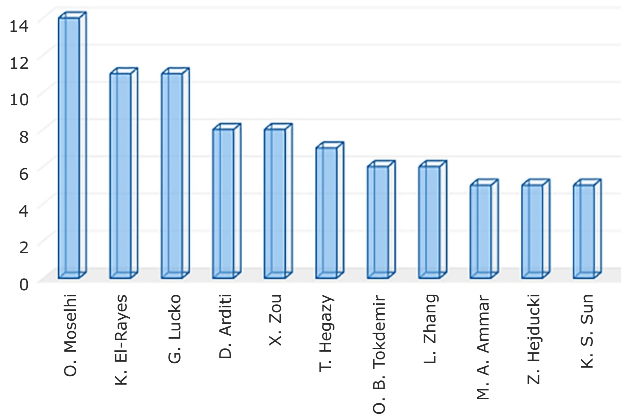

Figure 3. Distribution of publications by author

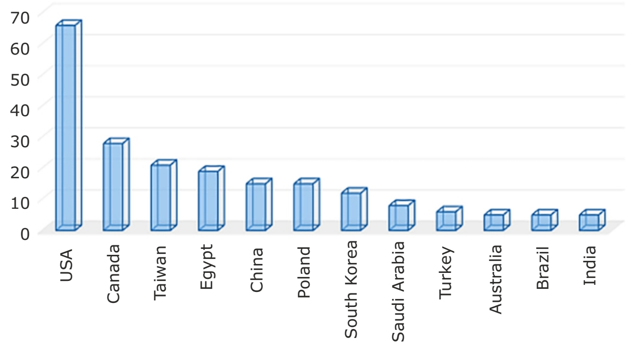

Figure 4. Distribution of publications by country

2.4. Material evaluation

2.4.1. Traditional scheduling techniques applied to repetitive construction projects

Some of the authors of the reviewed publications tried to adapt the classical tools of project management to the planning of repetitive projects. As early as in 1984 Jaafari argued for the applicability of the Critical Path Method (CPM) to scheduling repetitive construction projects (Jaafari, 1984). However, this was one of the few voices in favor of CPM. The vast majority of researchers argued against it (Chrzanowski & Johnston, 1986; Harmelink & Rowings, 1998; Harris & Ioannou, 1998).

O'Brien et al. (1985) put forward a development of CPM to adapt it to repetitive projects and illustrated its application in a large-scale project of constructing the King Khalid Military City housing facilities. Cole (1991) proved that CPM is more efficient with non-repetitive scheduling, whereas "linear methods" (such as Line of Balance) should be applied to repetitive projects. Kallantzis et al. (2007) developed principles for transforming models of linear projects into CPM network models. Extensions of CPM to serve repetitive projects were put forward by Ammar (2003), Russell and Wong (1993), Senior and Halpin (1998).

The traditional methods intended for scheduling repetitive construction projects base on a graphical representation of sequences of processes carried out by particular resources (contractors, crews) in the form of lines, and are often referred to as linear methods. Unlike other classic scheduling methods, they were created to support planning repetitive projects in the industry. One of them is the Line-of-Balance (LOB), developed at Goodyear in the early nineteen-forties, and then adapted by the U.S. Navy. The LOB models repetitive processes by a single lines on a graph. Unlike the Gantt chart, which shows the execution time of a process by the length of a bar representing the process, the LOB chart indicates the required performance of resources that execute the processes to meet the predefined due date by the slope of a segment of the line relative to the time axis). The LOB diagram efficiently visualizes the relationships between successive processes.

Arditi and Albulak (1986) presented applications of LOB to construction projects and analyzed its advantages (among others, clear visualization of sequential relationships between the processes and constraints on lead and lag times, and ease of analyzing changes in resource productivity/crew composition to elicit most efficient solution). The method was found not without drawbacks: the authors pointed that inaccuracies in the graphic representation of resource productivity accumulate and propagate over successive work units. Sarraj (1990) provided mathematical formalization of LOB. It thus ceased to be the purely graphic technique, and the results could be precisely calculated, and not just read from the chart. Gouda et al. (2017) developed LOB by introducing optimization algorithms for the assignment of multiskilled crews with the objective of assuring continuity of their employment; the functionality of the new method was illustrated using the example of constructing a four-kilometer section of a wastewater pipeline.

Arditi et al. (2002a) identified barriers limiting the applicability of LOB in construction and suggested directions for improving it. These included improving the visualization of LOB diagrams, enabling cost analysis, allowing for the learning effect and accelerating the execution of selected processes. They also pointed to a new type of process criticality, the need to deal with one-off (unrepeatable) processes in a LOB model and resource availability constraints and milestone constraints, finding a way to define the relationship between time and location of process execution, and develop an algorithm to reduce the project execution time. They actually developed LOB modifications to address some of these challenges (Arditi et al., 2001; Arditi et al., 2002b).

A development of LOB in the harmonization of repetitive processes was also undertaken in many other works (Agrama, 2011; Ammar, 2013; Damci, 2020; Hafez, 2004; Hegazy, 2001; Lutz & Hijazi, 1993; Suhail & Neale, 1994; Ungureanu et al., 2019; Zolfaghar Dolabi et al., 2014).

Another method intended for planning repetitive activities is the Linear Scheduling Method (LSM). Chrzanowski and Johnston (1986) applied it to scheduling the Research Triangle Park Road project in North Carolina. They described the advantages of this method, such clarity in conveying the project information, useful in monitoring the progress of works. The authors also emphasized the disadvantages of the method, especially the difficulty in modeling one-off processes that occasionally occur in repetitive projects.

An important development of LSM was proposed by Harmelink and Rowings (1998), who added functions enabling the planner to determine and control the critical path of the project. Indicating a critical sequence of processes (or fragments thereof), as in CPM, helped keep focus of construction management and expanded the range of possible applications of LSM.

Lucko and Gattei (2016) compared LOB and LSM, and pointed to LOB's capacity to work toward a target delivery rate and detect deviations in the "assembly" of activities, whereas LSM offers an easy way to account for time and resource buffers between processes, identify the critical path and various types of floats. The LSM method has also been addressed by Harmelink (2001) and Yamín and Harmelink (2001).

Harris and Ioannou (1998) created the Repetitive Scheduling Method (RSM) to facilitate control over repetitive projects. They introduced a counterpart of the CPM's critical path, called a controlling sequence. Mattila and Park (2003) proved that, in the case of simple projects, the LSM by Harmelink and Rowings (1998) and RSM define the same critical path.

Yang and Ioannou (2004) developed and programmed an RSM algorithm which eliminated tedious preparation of conventional LOB graphical models and enabled construction managers to quickly test different schedule options. A fuzzy extension of the RSM method was proposed by Maravas and Pantouvakis (2011), where uncertainties of estimating unit sizes and possible fluctuations in labor productivity were described by fuzzy sets. A great advantage of the presented approach, in contrast to the deterministic approach, is the consideration of risk in project planning. Another development of the RSM method was proposed by Ioannou and Yang (2016).

Hejducki (2003) developed the Time Couplings Method (TCM). Its family of models captures various aspects of the technological, resource-related and organizational relationships between processes and units. TCM models are formulated as one-criterion optimization problems of minimizing project duration that differ in the character of constraints. TCM I rules out the resource idle time, TCM II assures continuity of works in units, TCM III minimizes duration of the project with no constraints on resource idle time nor continuous work in plots, whereas TCM IV, V and VI introduce specific relationships (couplings) between the "work fronts" (units) and resources of preceding and consecutive processes (diagonal and reversed diagonal couplings). The algorithms of the proposed method enable the planner to determine the optimal sequence of units.

Other classic approaches to scheduling repetitive projects were RPM (Reda, 1990), MLS (Wang & Huang, 1998), POLO (Huang & Halpin, 2000), Systematic LSM (Mahdi, 2004), GMSM (Huang, 2006), UPSS (Bonnal et al., 2013), BRSM (Shim & Kim, 2014), and a method described by Hyun et al. (2021).

2.4.2. Resource-oriented repetitive scheduling

Schedules were originally developed as tools for harmonizing the work of numerous resources (employees, crews, individual machines or machine sets). The uniform, uninterrupted work of resources stays the project manager's vital concern: inefficiencies in resource utilization cause financial losses.

The literature on the subjects defines two basic problems: the Resource-Constrained Project Scheduling problem (RCPSP), and the Resource Levelling Problem (RLP). If undertaking the RCPSP problem was explicitly emphasized in the publication, it was assigned to the category analyzed in this section even if other criteria were applied to schedule optimization.

Most authors who addressed the need to harmonize the work of resources sought to ensure continuous engagement of resources. For instance, El-Rayes and Moselhi (1998) developed a two-stage scheduling algorithm for repetitive construction projects with the first stage aimed at satisfying the resource availability constraints and the sequential relationships between processes, and the second focused on the resource continuity. The algorithm allows interrupting the work flow in units to reduce the project execution time. A similar two-stage algorithm was used to determine the optimal crew composition (El-Rayes & Moselhi, 2001). Bonnal et al. (2005) applied Allen's relations to assure resource continuity. Huang and Sun (2006b, 2006a, 2009) put forward a planning and scheduling method based on identifying groups of repeatable processes; each group encompasses processes repeated in its set of units, typically different for each group. The method enables reducing project duration and keep the resources engaged. To find the solution of this complex problem, the authors developed a heuristic algorithm. García-Nieves et al. (2018) developed another method for scheduling resource-constrained repetitive construction projects aimed at assuring resource continuity; its novelty lies in the possibility of selecting process options – modes of their execution. Ammar (2020) modified LOB to enable minimizing project duration and allowing discontinuity in the execution of repetitive processes while maintaining continuity of resources. Ensuring resource continuity was also studied by Biruk and Jaśkowski (2009), Hafez (2005), Zhang et al. (2012) and Zou et al. (2021).

Some researchers adopted a different resource allocation strategy: instead of setting a constraint on continuous employment of the crews, they analyzed the efficiency of applying various measures to reduce downtime. For instance, Vanhoucke (2006) developed a recursive search algorithm looking for the optimal trade-off between project execution time and resource continuity. Kang et al. (2001) developed a mathematical model to assist construction managers in determining the optimal number of units and minimizing losses due to crews' idle time. The model by Altuwaim and El-Rayes (2018b) was intended to minimize the cost of crews' idle time together with its total scale and the duration of the project as a whole. Tomczak and Jaśkowski (2020) focused on the problem of reducing the downtime of the general contractor's in-house crews by subcontracting. Hassan and El-Rayes (2020) analyzed and quantified he impact of any unexpected process delays on the amount of downtime.

The repetitive project's resource leveling problem was considered, among others, by Georgy (2008), who employed a genetic algorithm to elicit a solution; the merits of the approach were illustrated by a case of highway construction. Damci et al. (2013a, 2013b) proposed a resource leveling method being an extension of LOB based on the concept of a "natural rhythm"; instead adjusting crew efficiency as in the classic LOB, the authors adjusted size of the crews. Application of this approach was also illustrated by a numerical example – a case of pipeline construction. Also Ammar (2022) aimed at providing resource leveling method to LOB projects; he looked for a trade-off between the project duration and the rate of resource idle time.

The resource leveling problem, where one of the objectives is minimizing the maximum number of resource units throughout the project, consists also in crew sizing. Dhanasekar (2000) minimized resource employment, defining it as the smallest possible number of workers required to complete a project within a defined period, using queueing theory. He also illustrated the merits of his model by solving a case of a project consisting of 320 buildings.

Another issue addressed in the literature is the problem of scheduling repetitive projects taking into account the work space availability. This problem was analyzed by Thabet and Beliveau (1994a, 1994b), who included the process-specific demand for work space to the constraints of their analysis, next to work continuity and variations in productivity rates of the crews. They expanded their model by allowing the use of different sets of resources for different processes (Thabet & Beliveau, 1997).

The issue of excessive crew size in a limited work space and its impact on productivity was addressed by Tao et al.

(2018). To solve this problem, the authors applied a nondominated genetic sorting algorithm modified by incorporating an electromagnetism-like mechanism (NSGAII-EM).

Lu and Li (2003) put forward their Resource-Activity Critical Path Method (RACPM) that integrates the process-based scheduling characteristic for CPM with resource-based planning. Yang and Chang (2005) created a stochastic repetitive scheduling support system that, next to the obvious considerations of resource availability constraints, accounts for the random character of disturbances in the supply chain. Operation of the model was checked using Monte Carlo simulations.

The resource-oriented and space-oriented repetitive scheduling in construction was undertaken by many other authors (Bakry et al., 2014; Bożejko et al., 2014; El-Rayes, 2001; Elhakeem & Hegazy, 2005; Hassan et al., 2021; Hassanein & Moselhi, 2004; Mattila & Abraham, 1998; Roofigari-Esfahan & Razavi, 2017; Tang et al., 2014a, 2014b, 2018).

2.4.3. Improving reliability of the scheduled completion time

Numerous publications on repetitive scheduling focus on improving reliability of scheduling results, in particular increasing the accuracy of predicting the project's actual time for completion. To do so, the authors strive to estimate the crew productivity rates (and so the duration of processes) more precisely. This is particularly important in the case of repetitive projects, where inaccuracies and errors cumulate into significant discrepancies between the as-planned scenario of project execution and the actual progress.

It was observed that crews, repeating the same type of work in consecutive units, improve their productivity. This phenomenon was called the learning effect. Possibly the first attempt to use this effect while scheduling civil engineering works were presented by Naresh and Jahren (1999). They constructed a schedule allowing for increase in the crew's production rates and conducted a sensitivity analysis to point to processes that are deciding for the project completion time. Lam et al. (2001) studied not only the learning, but also the forgetting effect (observed if crews' work is planned with interruptions) on the project duration and concluded that the effect on both project cost and duration was significant. Couto and Teixeira (2005) proposed a linear model with logarithmic coordinates to parametrize the learning process using data of two common construction processes. The model proved correct though the authors pointed that it needed further refinement if to be applied to scheduling, among others, to allow for unforeseen occurrences.

Zhang et al. (2014) developed a resource assignment model that allowed for the learning effect and met constraints of resource continuity and not exceeding the project due date. Jordan Srour et al. (2018) developed an optimization tool for estimating the duration of repetitive processes considering the learning effect. The application of the developed tool reduced labor costs by 28%.

Various learning effect-based extensions of LOB can be found also in the works of Ammar and Abdel-Maged (2018), Arditi et al. (2002b), Tokdemir et al. (2019). Biruk and Rzepecki (2017) studied the impact of learning on project schedules by means of simulations.

To improve the accuracy of estimates of repetitive process durations and project completion dates, factors affecting resource productivity other than the learning effect were considered. Duffy et al. (2012) developed a scheduling tool, Velocity 1.0, that accounted for the impact of time of the year and location on productivity rates. Baqerin et al. (2016) built their Weibull Evaluation and Forecasting Model to account for random character of process durations and enhance forecasting schedule performance of repetitive projects. Moreno et al. (2020) developed the Fixed Start Scheduling Method (FSM) that, by controlling the start dates of processes, was to ensure that the project due date is not exceeded. The method was tested by simulation on two cases, and its results were compared with results obtained using CPM and PERT. Application of FSM significantly reduced variability of the planned completion time of the project and increased the probability of completion before the due date. Zhang et al. (2020) proposed a new measure of repetitive schedule robustness expressing the schedule's ability to absorb random disruptions. The results of their analyses pointed that robustness of a schedule must be tested before the schedule is implemented.

Lucko (2008) introduced and then refined (Lucko, 2009, 2011a, 2011b; Lucko & Peña Orozco, 2009) the Productivity Scheduling Method (PSM). It uses singularity functions to model variability of crew performance. In spite of the model's relative simplicity, it proved efficient in constructing robust schedules of repetitive projects. Su and Lucko (2016) further developed the idea using singularity functions to model allocation of resources to processes, levels of resource utilization, and harmonization of work of multiple crews.

Many researchers have attempted to increase the reliability of meeting planned deadlines for repetitive processes and the resilience of schedules to random events by introducing time buffers in schedules. Rogalska and Hejducki (2007) used "feeding buffers" and "project buffers" (as defined in Goldratt's Critical Chain) to test the effect of their size on the total project duration. González et al. (2009) used buffers to reduce the negative impact of productivity fluctuations and presented the advantages of buffering using two case studies. Bakry et al. (2016) proposed a tool for optimizing schedules in terms of cost and duration in risky environment. Time buffers were applied to improve reliability of the scheduled completion date. To model random character of the schedule's input, they used fuzzy set theory instead of statistical inferences on distribution parameters based on project records. S. Lee et al. (2016) proposed application of three types of buffers (time, location and process) to protect the schedule against inaccuracies in identification of relationships between processes.

The reliability of schedules was the object of interest of many other researchers (Abbasnezhad et al., 2020; Duffy et al., 2011; Katsuragawa et al., 2021; Lee, 2016; Lucko et al., 2014a; Salama et al., 2018).

2.4.4. Minimizing duration of repetitive projects

Minimizing project duration is typically the key aim of the scheduling process. Quickly delivered projects mean economic benefits for both the contractor and the client. However, if the deadlines prove too tight, a failure to meet them results in the contractor's paying delay damages and loosing reputation, and disturbs the client's plans towards the effect of the project. Therefore, the ways of "reasonable" minimization of the project duration belong to the most frequently addressed issues in project management research. Exact algorithms are proposed for solving simpler models, but real-scale projects prove too complex. Therefore, heuristic and metaheuristic algorithms are employed to find acceptable solutions. One of the most frequently employed algorithms used to find pseudo-optimal solutions to repetitive scheduling problems are evolutionary algorithms. Leu and Hwang (2001) used a genetic algorithm do solve a model for minimizing duration of production of a set of precast concrete elements; the model assumed that resources (cranes and formwork sets) can be shared to maximize production capacities. Nassar (2005) used genetic algorithms in optimizing resource allocation in repetitive construction projects with the objectives to minimize the project duration and the idle time of crews. Hsie et al. (2009) used evolutionary strategies to solve a model of a repetitive project where the units were defined not according to their geometric dimensions, but the workload related with processes. This model minimized the project's completion time considering resource availability and continuity of their work.

Some authors resorted to simpler heuristics to find pseudo-optimal solutions of minimizing repetitive project durations. For instance, Zhang et al. (2006) used a tree-based permutation procedure to determine all solution alternatives and then simple heuristics to determine the ranking of each solution. Their method for scheduling repetitive construction projects takes into account the limited availability of resources and allows for multiple options of process execution. Tran et al. (2020) used a hybrid algorithm called the fuzzy clustering artificial bee colony approach for schedule optimization. Experimental results indicated that, in comparison to other algorithms, the proposed method produces, on average, the shortest execution time and the lowest deviation of the optimal solution.

The problem of optimizing repetitive schedules was modeled as a linear program and solved by means of general-purpose solvers. Liu and Wang (2012) used this method to compose a schedule of the shortest duration dedicated for a case with multi-skilled crews (so resources able to execute more than one type of construction process). Using multi-skilled crews helped reduce resource idle time.

Russell and Caselton (1988) formulated the construction scheduling problem as a dynamic programming problem. They analyzed various suboptimal solutions in order to identify schedules that better satisfy the decision-maker's expectations.

Jaśkowski and Biruk (2019) adapted the flow shop problem known from production engineering to repetitive schedules. They solved the model using Minimum Hamiltonian Cycle algorithm.

Fan and Tserng (2006) implemented soft relationships between processes in the network model of the project to minimize the project makespan and ensure continuity of resources. Cho et al. (2013) developed an approach to improve the work space utilization to increase the productivity of workers and, at the same time, reduce the project duration. Bakry et al. (2014) developed a computer-based system to assist the planner in reducing construction project makespans by enabling the planner to break down processes into simpler operations and pointing to those whose acceleration has the strongest effect on the overall project duration. Acceleration of operations identified this way can be achieved by adding extra crews, working overtime, using double shift or weekend work.

D. Lee et al. (2016) proposed TACT and enhanced-TACT (both being extensions of LOB) to schedule repetitive projects more conveniently; an analysis of a large sample of case studies indicated that, by employing enhanced-TACT, the average project makespan could be reduced by 25% compared with as-scheduled makespans of projects according to their original schedules.

Minimizing repetitive project makespan was also the key objective of the following publications out of the set selected for the analysis: Hassanein and Moselhi (2005), Lucko et al. (2014b), Podolski (2017), Radziszewska-Zielina and Sroka (2018), Suresh et al. (2011), Zhang and Qi (2012).

2.4.5. Minimizing cost of repetitive projects

Another important criterion of schedule optimization is the cost. Searching for economies at the construction stage of the project is a key aspect of management. Therefore, this issue has been frequently addressed by researchers.

One of the earliest works in this area includes a paper by Moselhi and El-Rayes (1993a), who developed a dynamic programming model to minimize the construction cost of a project considering the effects of weather and a learning curve. An example was used to illustrate the effect of these factors on the cost of construction and to compare the results with those obtained by means of methods focused on minimizing the project makespan. The authors proved that minimizing the project duration does not guarantee minimum construction cost. The authors continued their studies to assist planners in decision making (Moselhi & El-Rayes, 1993b).

Hegazy and Wassef (2001), to minimize the total cost of project execution, developed a model for synchronizing the work of crews and improving its continuity integrated with CPM and LOB. Calculations are based on an evolutionary algorithm and a spreadsheet was used to present the solutions. As a result, the tool was easy to use, and the solutions close to the global optimum. The genetic algorithm was also used to find solutions to a model that minimized the total costs (direct costs, indirect costs, contractual penalties and bonuses for early completion, and the cost generated by relocation of crews) of implementing a set of facilities (Hegazy et al., 2004). Similarly, the genetic algorithm was the core of a computer system presented by Hegazy and Kamarah (2008). Here, to improve the model's flexibility, the authors decided to propose three modes of each process to select from in the course of the analysis, the modes differing in process execution methods – and thus in duration and cost.

A genetic metaheuristic algorithm was also employed in the model by Ali and Elazouni (2009), where the optimization objective was to maximize the profit under specific project funding conditions. The model draws from both CPM and LOB, and was implemented in MS Excel 2003. A thorough sensitivity analysis of this model gave insight into the relationship between the credit limits and the total amount of idle time, number of crews, direct costs, funding costs, and the overall construction duration.

A different idea of minimizing construction cost in the course of scheduling process, also based on genetic algorithms, was presented by Huang et al. (2016). They considered alternative modes of process execution and assumed that some sequential relationships between them can be relaxed (soft relationships), and put a constraint completing the works no later than at a predefined due date. They proved that the total construction cost is highly dependent on the sequence of processes, and the optimal sequence is highly dependent on the due date.

Profit maximization was the scheduling objective in analyzes presented by Abdallah and Alshahri (2019), who also used genetic algorithms. The results obtained from the case study showed a 21% increase in investor profit, when compared with the original schedule.

Podolski and Sroka (2019) applied a simulated annealing algorithm to solve a linear program to minimize the construction costs. The method verification studies confirmed high efficiency of the approach.

Fan et al. (2012) also decided to consider soft relationships in their model of repetitive project. In contrast to most researchers, who assumed that the sequence of processes should be fixed, and following observations of construction practices, they decided that the sequence of the crew's moving from unit to unit does not need to be fixed. With the sequence constraints relaxed, they generated even more advantageous schedules: of shorter makespans and lower costs.

The problem of scheduling repetitive projects with the objective of minimizing cost was also considered in other works from the analyzed sample (Bożejko et al., 2012; Moselhi et al., 2016; Shtub et al., 1996; Zou et al., 2021).

2.4.6. Multicriteria optimization of repetitive construction schedules

Numerous works on the scheduling repetitive construction projects are based on a multicriteria approach. Adeli and Karim (1997) presented a neural dynamics model to find best time-cost trade-off solutions with resource continuity constraints, enabling the user to adjust crew composition and changes in crew performance. Ezeldin and Soliman (2009) developed an approach to minimize the construction time and cost in risk conditions. A genetic algorithm was used to find suboptimal solutions, and dynamic programming was used to search the neighborhood of the best results. Minimization of time, and/or cost was also studied by Long and Ohsato (2009). The model presented in this work accounted for crews' work continuity, allowed the planner to define process attributes (interruptible or not) and differentiate relationships between their direct costs and durations. A similar problem was considered by Moselhi and Hassanein (2003). Hyari et al. (2009) sought a trade-off between time and indirect costs or the total cost. The problem of bicriteria optimization of the time and cost of repetitive projects has also been addressed in the works by Cho et al. (2010), Heravi and Moridi (2019), Lee et al. (2010), Rogalska et al. (2008), Tran et al. (2019), Zhang et al. (2015), and Zou et al. (2017).

Hyari and El-Rayes (2006) developed a repeatable project scheduling model to maximize the resource continuity and minimize the project makespan. This model consists of three levels: the first one calculates the duration of the project and the level of resource continuity, the second looks for pseudo-optimal solutions, and the third creates a ranking of solutions given the defined requirements of the decision maker. This makes it easier for the decision maker to choose the best schedule from the point of their preferences. The same optimization criteria are adopted by Altuwaim and El-Rayes (2018a). The scheduling method presented there includes four phases: determination of the earliest possible start dates for processes, calculation of floats, strict work continuity, and performance evaluation. The presented approach facilitates the decision-maker in generating alternative schedules of minimum makespan and analyze their impact on the total cost.

Ipsilandis (2007) developed a linear programming model for minimizing the costs of failing to meet the due date together with the costs generated by idle time of crews. Similar criteria (profit maximization and minimization of crew idle time) were adopted by Liu and Wang (2009). The proposed two-step method enables the determination of the optimal schedule and composition of crews for satisfying the financial needs of contractors. The same authors Liu and Wang (2007) developed a mathematical programming model for resource allocation with various objectives: minimizing the project duration or minimizing idle time, and under various constraints, for instance limited cost of subcontracted work.

Abd El Razek et al. (2010) presented a developed a computer system to support the selection of the optimal solution considering three criteria: time, cost, and quality of works. The same criteria were considered and optimized by Wang et al. (2021); the analyzes were expanded by including continuity of works (Tran et al., 2018). Multiple optimization criteria (minimizing project duration, resource leveling, and reducing process interruptions) were also considered by Agrama (2014); the strength of this model is clarity and readability.

A four-criteria (duration, cost, interruptions, and delay) optimization model was presented by Eid et al. (2021). Tomczak (2019) puts forward a conceptual deterministic model for harmonizing the execution of non-uniform processes of a project involving erection of a number of buildings, intended for reduction of project makespan and work interruptions. The relative importance of the optimization criteria was to be set by the decision-maker. The author provided mathematical formulation of the problem of the crew allocation and sequencing of units and explained its operation using a case study. The proposed method was found efficient in improving resource utilization rates. A number of optimization criteria (time, cost, and work interruptions) are considered in the work by Salama and Moselhi (2019) assuming non-deterministic conditions.

Cheng et al. (2005) developed a hybrid algorithm combining heuristic and genetic approaches to minimize the unit cost or maximize the productivity of a production system. This algorithm was intended to assist construction managers in resource allocation, thus improving the quality of schedules.

Multi-criteria approaches for planning repetitive construction projects have also been applied by Arabpour Roghabadi and Moselhi (2021) and García-Nieves et al. (2019).

2.4.7. Other models for scheduling repetitive projects

Many authors attempted to develop comprehensive repetitive scheduling support systems that did not fit into any of the previous categories. For instance, Russell (1985) created a computer aided construction management system for tall buildings. It combined the features of activity-on-node network modeling and linear methods. Yi et al. (2002) addressed their scheduling support system to inexperienced construction managers to help them build a network model and optimize it; a case study of an 18-story building was an illustration of this system's capabilities: its application helped reduce the as-planned construction time by 42%. Huang and Sun (2005) developed a system to support repetitive scheduling that accounted for sequential relationships between the processes, and the possibility to use different crews to the same process in different units. It helped improve resource continuity and accounted for time and cost of crews. This system had a user-friendly interface and generated the schedule in both numerical and graphical form, the latter as a time-location diagram (AutoCad graphics) and a network model executed in MS Project. The Advanced Linear Scheduling System (ALISS) by Tokdemir et al. (2006) accounted on constraints for project time and resource and working space availability. The results were generated as a histogram and a cumulated distribution of project costs. Another system, this time based on soft relationships between processes, was proposed by Cho et al. (2011). A system dedicated for scheduling tunnelling projects was presented by Abdallah and Marzouk (2013). It estimated the time and cost of the project, and helped select the most convenient schedule according to numerous criteria, including: minimizing the duration and cost and maximizing resource utilization rates. Hajdasz (2014) developed the Monolithic Construction Computer Aided System that facilitated synchronizing operations of balanced resource sets, and supported the decision-maker in creating scenarios of project execution strategies in anticipation of disruptions.

Kavanagh (1985) built a simulation model based on queueing theory to aid in time and cost management of repetitive construction projects. The model considers crew and equipment availability, the learning effect, and the impact of weather.

Zhang et al. (2002) applied simulation to plan repetitive projects, in particular those constrained by scarce resources and a large number of relationships between processes. One of the greatest benefits of the approach used is better utilization of the resources.

Sawhney et al. (2003) used Petri nets. This enabled dynamic allocation of resources and facilitated capturing the stochastic nature of processes. Petri nets were also used in the work by Biruk and Jaśkowski (2008) to assist in the management of repetitive construction projects and resource allocation.

Dzeng et al. (2004) proposed a computer system to standardize repetitive scheduling of projects delivered by multiple contractors. The system was claimed to reduce the number of planning errors and speed up the scheduling process.

Han et al. (2012) aimed at eliminating non-value-adding effort to avoid delays and cost overruns.

Hegazy et al. (2014) developed a decision support system to be applied at the construction stage of linear projects (i.e., for monitoring and control) by automated recording of the as-built information and schedule updates. Compared to traditional methods, where the schedule is just a passive report used for presentation purposes, the developed system transforms it into a rich medium for documentation, visualization, analysis and decision making.

Lucko et al. (2016) adapted slip charts invented for planning projects in the space industry to visualize schedules of repetitive construction projects. They added extra features necessary for the new application: buffers, process criticality, and process floats. The geographic information system (GIS) was employed to improve scheduling visualization and facilitate construction project planning in the works by Sharma and Bansal (2018) and Tomar and Bansal (2019, 2020, 2022).

Other specific scheduling problems of repetitive construction projects have also been addressed in the following works: (Eiris Pereira & Flood, 2017; El-Rayes et al., 2002; Handa & Barcia, 1986; Hegazy et al., 2020; Hu & Mohamed, 2014; Russell et al., 2009; Sharma et al., 2009).

3. Summary

The problem of harmonizing repetitive processes in construction projects has been repeatedly taken up by the research community. This interest has two reasons. On the one hand, the problem is complex and hard to solve, a great challenge for researchers, which made them eager to undertake it. On the other hand, this is a practical problem: project managers still have no adequate scheduling tools. So far, the researchers have solved many specific problems of process harmonization in repetitive ventures. These included improving resource utilization rates, resource leveling, dealing with resource availability constraints, increasing the robustness of schedules, more accurate prediction of the course of project execution, minimizing the duration and/or cost of works, improving the visualization of schedules, developing multi-criteria models, using metaheuristic algorithms, especially genetic, to reduce the time to solve complex models of practical problems. For this purpose, the researchers expanded the traditional construction scheduling methods as well as linear scheduling methods used for industrial production planning. However, many new models and algorithms tailored for repetitive construction have been proposed.

The literature review points to several trends in repetitive scheduling research. The basic observation is that the number of publications on the subject is growing. Initially, the authors focused on the adaptation of traditional planning methods to the management of repetitive construction projects. Nowadays, topics related to resource-oriented planning, increasing reliability of schedules under random disturbances, and multi-criteria approaches to the planning of repetitive construction projects are gaining attention. This is related to the tendencies observed throughout the world science – the attempts to consider problems in a holistic and stochastic way, as well as the growing role of human capital considered as a basic asset of the enterprise. More and more advanced algorithms, e.g., metaheuristic algorithms are used to find solutions to scheduling problems. Initially, the genetic algorithm was most frequently employed to search for the most satisfactory solutions. Recently, the research community applies advanced and sophisticated algorithms such as Symbiotic Organisms Search or various hybrid approaches. Knowledge-based approaches and those using various mathematical algorithms, e.g., Minimum Hamiltonian Cycle Search or Weibull distribution, are also gaining popularity.

4. Discussion

Scheduling repetitive construction projects is a problem attracting more and more attention of both researchers and practitioners. Most construction projects are at least partly repeatable. From the point of contractors, the ability to optimize schedules offers a relatively cheap way of finding economies and gaining advantage in a highly competitive market. However, optimizing repetitive schedules is a challenge, if only because of the number of constraints worth considering. Construction projects are especially prone to risks. Unfortunately, most of the scheduling methods proposed by the literature are deterministic. This translates into low robustness of schedules: they easily expire.

Many publications focused on a particular scheduling aspect. In practice, there are no such isolated problems: projects are implemented comprehensively, with the whole spectrum of case-specific constraints. The same is true for the criteria of schedule quality: the decision-makers typically have multiple objectives, whereas most of the papers were devoted to single-criterion scheduling problems.

Considering the analyzed sample of papers, there is an impression that the authors put forward a complete algorithm, ready to be implemented in practice, and the decision-maker to use it is treated merely as a recipient of the solution, not a co-creator. As the planners wish to make informed decisions (it is their money and reputation at stake), they may want to include and exclude constraints, modify the assumptions, and set their case-specific objectives. The decision-maker needs towards the scheduling results may remain unverbalized and cannot be addressed by most of the solutions proposed to date. Therefore, complex scheduling algorithms can get less uptake than expected. There is evidence of the construction practitioners' reluctance towards novelty scheduling tools (Tomczak & Jaśkowski, 2021).

Visualization of repetitive schedules remains a problem all the time. Due to a large number of processes repeated in multiple units, the "classic" bar charts become impractical due to the sheer size of the complete list of tasks. On the other hand, LOB diagrams, by far more concise, do not present execution constraints precisely enough; there is no possibility to change the order of units, and above all, there is no possibility to point to complex sequential dependencies (technological, organizational) between individual processes in different units.

Application of systems supporting the planning of repetitive construction projects that rely on data collected during past projects seems to be limited, if only because of difficulties in obtaining the input. Construction projects usually take a long time, so the data collection process is slow. As the construction methods and machines evolve rapidly, construction projects are highly unique (individual designs, the impact of location-specific factors, the impact of organization of the project team, etc.) and their progress is strongly affected by unforeseen, hardly controllable, and transient disturbances, the past project's records may be an unreliable source of information for future ventures. Moreover, construction enterprises must rely on in-house data (team productivity figures are considered sensitive information). For this reason, this type of input is often not credible enough. Despite these difficulties, it appears that the benefits of systems using data collected from previous ventures are so great that their use is insufficient.

Additionally, managers of repetitive construction projects often have considerable knowledge and experience with such projects. Few of the existing methods to support the planning of repetitive construction projects use this type of information (often difficult to verbalize). They are particularly valuable because of the difficulties in collecting reliable data from past projects mentioned above. To capture the imprecise character of verbally expressed preferences it is reasonable to apply modern tools drawing from the fuzzy set theory, such as the neutrosophic linguistic sets, hesitant fuzzy linguistic sets or probabilistic linguistic sets.

Building Information Modelling is a technology that strongly changes the construction industry and re-evaluates the roles of project participants. It is expected to improve the quality of built assets and increase effectiveness of management of the whole investment process, including execution of construction works by enabling multi-range analyses, more efficient communication between project participants and greater control over information flow. However, the systems for planning repetitive construction projects ignore the impact and importance of this technology. The future construction project planning systems are expected to be fully integrated with BIM technology.

By definition, repetitive construction projects consist of processes that are repeated unit by unit, often many times within the same project. However, apart from them, there are also one-off processes. Many of the existing methods, such as LOB, do not allow for such processes. These methods also often do not allow for differences in the size of units, so the fact that there may exist differences in the resource demand of the same process in different units. Such differences are natural in most real-life projects. In addition, the division of the project into units is not always obvious and poses another decision problem. It is also possible that the units should be defined differently for different processes. The existing scheduling support systems for repetitive construction projects assume that the subdivision of the project into units was done in advance, and do not assist the decision-maker in the identification of the units.

It also seems that planning support systems for repetitive construction projects may evolve towards a different “understanding of repetitiveness”: the division into units may be different for different processes. A promising approach is to identify “groups of sub-processes” that are repeated in the units identified only for them, with the units being of different sizes. A more flexible approach to unit definition would allow the planner to model more complex relationships between units than the assumption of a serial technological order of their execution.

So how should the repetitive scheduling support system of the future look like? Certainly, it should be simple: easy to use even for those without technical or IT expertise, with an intuitive interface, and easily interpretable graphical representation of the results. It is notable that all tools that have been widely adopted in the practice of construction projects are simple to use and interpret.

It should also be adaptable to the needs of a particular decision-maker, i.e., the manager of the repetitive construction project. A system that generates black-box solutions without the involvement of the decision-maker will most likely never be widely accepted and used. Repetitive construction projects cover a wide spectrum of different projects: from road construction to skyscrapers and housing development. Therefore, it should be possible to easily change settings to correspond to a particular case. Flexibility in adapting the system to the preferences of the decision-maker (optimization criteria, constraints, the existence of non-repeatable processes) and its simplicity (operation and graphic interpretation) seem to be key prerequisites in the uptake of the system by users.

A scheduling support system should also generate robust solutions – schedules that keep representing an economically justified plan of works regardless of the typical disturbances like crew productivity fluctuations or occasional bad weather. By using data collected from previous construction projects, knowledge of construction management, and modern tools it is possible to minimize the impact of risks on the schedule of construction projects.

Last but not least, each repetitive construction project contains a number of problems that need to be solved, so the developed system should be holistic, covering as broadly as possible the issue of support for planning repetitive construction projects. State-of-the-art computational algorithms such as hyperheuristic algorithms can help in this process.

Conclusions

In this paper, an attempt was made to collect and analyze a representative sample of research papers on scheduling repetitive construction projects using a structured methodology. Then, to organize information on the existing approaches to this problem and on methods used to solve it, the sources were classified into seven categories: traditional methods and tools for scheduling repetitive construction projects, resource-oriented scheduling of repetitive construction projects, improving the reliability of the scheduled completion time, minimizing the duration of repetitive construction projects, minimizing the cost of repetitive construction projects, multi-criteria approaches to planning repetitive construction projects, and other approaches to scheduling repetitive construction projects. On this basis, the authors intended to elicit scheduling issues still calling for refinement and to point to directions of future research.

One of the objectives of the paper was to indicate the progress in scheduling repetitive construction projects over time. The efforts of numerous scholars changed the planning methods from unsophisticated adaptations of simple planning techniques (such as CPM), not intended for projects of this type, to advanced algorithms based on complex metaheuristics. Despite the evidence of considerable improvement in repetitive scheduling methods, the authors managed to identify areas for their further development.

The authors hope that this study will contribute to better identification of existing problems in planning repetitive construction projects and faster development of decision support systems, eagerly anticipated by the construction practitioners.

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Author contributions

MT and PJ both contributed in organizing the research and setting up the theoretical background; description of the problem, MT; data collection, MT.; MT and PJ both were responsible for data interpretation; MT wrote draft of the of the article. MT and PJ both contributed to the writing of this paper.

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APPENDIX

Table A.1. Allocation of articles

Traditional repetitive project scheduling methods and tools			
Jaafari A.	1984	Ammar M. A.	2003
O'Brien J. J., Kreitzberg F. C., Mikes W. F.	1985	Hejducki Z.	2003
Arditi D., Albulak M. Z.	1986	Mattila K. G., Park A.	2003
Chrzanowski E. N., Jr., Johnston D. W.	1986	Hafez S. M.	2004
Reda R. M.	1990	Yang I.-T., Ioannou P. G.	2004
Sarraj Z. M. A.	1990	Mahdi I. M.	2004
Cole L. J. R.	1991	Huang Y. C.	2006
Lutz J. D., Hijazi A.	1993	Kallantzis A., Soldatos J., Lambropoulos S.	2007

Continue of Table A1

Russell A. D., Wong W. C. M.	1993	Biruk S., Jaśkowski P.	2009
Suhail S. A., Neale R. H.	1994	Agrama F. A. E.-M.	2011
Harmelink D. J., Rowings J. E.	1998	Maravas A., Pantouvakis J.-P.	2011
Harris R. B., Ioannou P. G.	1998	Ammar M. A.	2013
Senior B. A., Halpin D. W.	1998	Bonnal P., Baudin M., De Jonghe J.	2013
Wang C.-H., Huang Y.-C.	1988	Shim E., Kim B.-C.	2014
Huang R.-Y., Halpin D. W.	2000	Zolfaghar Dolabi H. R., Afshar A., Abbasnia R.	2014
Arditi D., Tokdemir O. B., Suh K.	2001	Ioannou P. G., Yang I.-T.	2016
Harmelink D. J.	2001	Lucko G., Gattei G.	2016
Hegazy T.	2001	Gouda A., Hosny O., Nassar K.	2017
Yamín R. A., Harmelink D. J.	2001	Ungureanu L. C., Hartmann T., Serbanoiu I.	2019
Arditi D., Tokdemir O. B., Suh K.	2002a	Damci A.	2020
Arditi D., Sikangwan P., Tokdemir O. B.	2002b	Hyun H., Jung M., Yoon I., Lee H.-S., Lee J.	2021
Resource-oriented scheduling of repetitive construction projects			
El-Rayes K., Moselhi O.	1988	Huang R.-Y., Sun K.-S.	2009
Thabet W. Y., Beliveau Y. J.	1994a	Zhang L., Zou X., Chen X.	2012
Thabet W. Y., Beliveau Y. J.	1994b	Damci A., Arditi D., Polat G.	2013a
Thabet W. Y., Beliveau Y. J.	1997	Damci A., Arditi D., Polat G.	2013b
Mattila K. G., Abraham D. M.	1998	Bożejko W., Hejducki Z., Uchroński M., Wodecki M.	2014
Dhanasekar M.	2000	Tang Y., Liu R., Sun Q.	2014a
El-Rayes K.	2001	Tang Y., Liu R., Sun Q.	2014b
El-Rayes K., Moselhi O.	2001	Roofigari-Esfahan N., Razavi S.	2017
Kang L. S., Park I. C., Lee B. H.	2001	Altuwaim A., El-Rayes K.	2018
Lu M., Li H.	2003	García-Nieves J. D., Ponz-Tienda J. L., Salcedo-Bernal A., Pellicer E.	2018
Hassanein A., Moselhi O.	2004	Tang Y., Sun Q., Liu R., Wang F.	2018
Bonnal P., Gourc D., Hameri A.-P., Lacoste G.	2005	Tao S., Wu C., Sheng Z., Wang X.	2018
Elhakeem A., Hegazy T.	2005	Ammar M. A.	2020
Hafez S. M.	2005	Ammar M. A.	2022
Yang I.-T., Chang Ch.-Y.	2005	Hassan A., El-Rayes K.	2020
Huang R.-Y., Sun K.-S.	2006a	Hassan A., El-Rayes K., Attalla M.	2021
Huang R.-Y., Sun K.-S.	2006b	Tomczak M., Jaśkowski P.	2020
Vanhoucke M.	2006	Zou X., Wu G., Zhang Q.	2021
Georgy M. E.	2008		
Increasing repetitive schedule's reliability and robustness against random disruptions			
Naresh A. L., Jahren C. T.	1999	Bakry I., Moselhi O., Zayed T.	2016
Arditi D., Tokdemir O. B., Suh K.	2001	Baqerin M.H., Shafahi Y., Kashani H.	2016
Lam K. C., Lee D., Hu T.	2001	Lee J.-S.	2016
Couto J. P., Teixeira J. C.	2005	Lee S., Lee S., Son J.	2016
Rogalska M., Hejducki Z.	2007	Su Y., Lucko G.	2016
Lucko G.	2008	Biruk S., Rzepecki Ł.	2017
González V., Alarcón L.F., Molenaar K.	2009	Ammar M. A., Abdel-Maged A. F.	2018
Lucko G.	2009	Jordan Srour F., Kiomjian D., Srour I.M.	2018
Lucko G., Pea Orozco A. A.	2009	Salama T., Salah A., Moselhi O.	2018
Duffy G.A., Oberlender G. D., Seok Jeong D. H.	2011	Tokdemir O.B., Erol H., Dikmen I.	2019
Lucko G.	2011a	Abbasnezhad K., Ansari R., Mahdikhani M.	2020
Lucko G.	2011b	Moreno F., Orozco F., Rojas O., Senior B., Poshdar M., Forcael E.	2020
Duffy G., Woldesenbet A., Jeong D. H. S., Oberlender G. D.	2012	Zhang, L., Dai, G., Zou, X., Qi, J.	2020
Lucko G., Alves T. D. C. L., Angelim V. L.	2014a	Katsuragawa C.M., Lucko G., Isaac S., Su Y.	2021
Zhang L., Zou X., Kan Z.	2014		

End of Table A1

Minimizing the duration of repetitive projects			
Russell A. D., Caselton W. F.	1998	Zhang L., Qi J.	2012
Leu S.-S., Hwang S.-T.	2001	Cho K., Hong T., Hyun C. T.	2013
Hassanein A., Moselhi O.	2005	Bakry I., Moselhi O., Zayed T.	2014
Nassar K.	2005	Lucko, G., Said, H.M.M., Bouferguene, A.	2014b
Fan S.-L., Tserng H. P.	2006	Lee D., Kim D.-S., Kim G.-H., Kim S.	2016
Zhang H., Li H., Tam C. M.	2006	Podolski M.	2017
Hsie M., Chang C.-J., Yang I.-T., Huang C.-Y.	2009	Radziszewska-Zielina E., i Sroka B.	2018
Suresh M., Dutta P., Jain K.	2011	Jaśkowski P., Biruk S.	2019
Liu S.-S., Wang C.-J.	2012	Tran D.-H., Chou J.-S., Luong D.-L.	2020
Minimizing the cost of repetitive projects			
Moselhi O., El-Rayes K.	1993	Bożejko W., Hejducki Z., Wodecki M.	2012
Moselhi O., El-Rayes K.	1993	Fan S.-L., Sun K.-S., Wang Y.-R.	2012
Shtub A., LeBlanc L. J., Cai Z.	1996	Moselhi O., Bakry I., Alshibani A.	2016
Hegazy T., Wassef N.	2001	Huang Y., Zou X., Zhang L.	2016
Hegazy T., Elhakeem A., Elbeltagi E.	2004	Abdallah M., Alshahri A.	2019
Hegazy T., Kamarah E.	2008	Podolski M., Sroka B.	2019
Ali M.M., Elazouni A.	2009	Zou X., Zhang L.	2020
Multi-objective approach to repetitive projects scheduling			
Adeli H., Karim A.	1997	Agrama F. A. E. M.	2014
Moselhi O., Hassanein A.	2003	Zhang L., Zou X., Qi J.	2015
Cheng T.-M., Feng C.-W., Chen Y.-L.	2005	Zou X., Fang S.-C., Huang Y.-S., Zhang L.-H.	2017
Hyari K., El-Rayes K.	2006	Altuwaim A., El-Rayes K.	2018
Rogalska M., Bożejko W., Hejducki Z.	2008	Tran D.-H., Luong-Duc L., Duong M.-T., Le T.-N., Pham A.-D.	2018
Ipsilandis P. G.	2007	García-Nieves J. D., Ponz-Tienda J. L., Ospina-Alvarado A., Bonilla-Palacios M.	2019
Liu S.-S., Wang C.-J.	2007	Heravi G., Moridi S.	2019
Ezeldin A. S., Soliman A.	2009	Salama T., Moselhi O.	2019
Hyari K. H., El-Rayes K., El-Mashaleh M.	2009	Tomczak M.	2019
Liu S.-S., Wang C.-J.	2009	Tran D.-H., Chou J.-S., Luong D.-L.	2019
Long L.D., Ohsato A.	2009	Wang T., Abdallah M., Clevenger C., Monghasemi S.	2021
Abd El Razek R.H., Diab A. M., Hafez S. M., Aziz R. F.	2010	Arabpour Roghabadi M., Moselhi O.	2021
Cho K., Hong T., Hyun C.	2010	Eid M.S., Elbeltagi E.E., El-Adaway I.H.	2021
Lee H.-S., Roh S., Park M.-S., Ryu H.-G.	2010		
Other approaches to scheduling repetitive construction projects			
Kavanagh D. P.	1985	Cho K., Hong T., Hyun C.	2011
Handa V. K., Barcia R. M.	1986	Han S., Lee S., Peña-Mora F.	2012
Russell A. D.	1985	Abdallah M., Marzouk M.	2013
El-Rayes K., Ramanathan R., Moselhi O.	2002	Hajdasz M.	2014
Yi K. J., Lee H.-S., Choi Y. K.	2002	Hu D., Mohamed Y.	2014
Zhang H., Tam G.M., Shi J. J.	2002	Hegazy T., Abdel-Monem M., Saad D. A.	2014
Sawhney A., Mund A., Chaitavatputtiporn T.	2003	Lucko G., Araújo L. G., Cates G. R.	2016
Dzeng R.J., Wang W. C., Tserng H. P.	2004	Eiris Pereira R., Flood I.	2017
Huang R.-Y., Sun K.-S.	2005	Sharma S., Bansal V. K.	2018
Tokdemir O. B., Arditi D., Balcik C.	2006	Tomar A., Bansal V. K.	2019
Biruk S., Jaśkowski P.	2008	Tomar A., Bansal V. K.	2020
Russell A., Staub-French S., Tran N., Wong W.	2009	Tomar A., Bansal V. K.	2022
Sharma H., McIntyre C., Gao Z., Nguyen T.-H.	2009	Hegazy T., Saad D. A., Mostafa K.	2020