Dynamic scheduling in construction projects

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Abstract. The aim of the study is to investigate the theoretical foundations of dynamic scheduling in construction projects and provide some recommendations for further research. While the theory of "static" scheduling is the most developed, much less attention is paid to "dynamic" scheduling. At the same time, research shows that "dynamic" scheduling is most suitable for construction industry, especially for complex and large projects. To achieve the aim of the study, such tasks as (1) the formulation of the problem associated with insufficient elaboration scheduling dynamism and complexity issues in construction; (2) a review of the scientific literature on this problem; (3) the formation of some possible directions for the development of the theory of dynamic scheduling, were solved. Research methods are: analysis, synthesis, review of scientific literature. The result of the study is recommendations on one of the directions of dynamic scheduling theoretical foundations' development in construction projects, namely scheduling visualization techniques on the example of the "spring chart" developed by the author. The relevance of the results is due to the fact that the developed recommendations can be useful to researchers in the field of project scheduling for a systematic study of the problem.

1. Introduction

Construction projects are often characterized by significant delays. Such delays lead to negative consequences for the project stakeholders, i.e. financial losses, freezing of investments, shifting the payback point, deterioration of reputation, etc. The problem has been considered in numerous studies. The vast majority of them are devoted to planning deadlines and leveling deviations from the initial schedule during the construction. The approaches used in these studies can be characterized as "static", since they do not imply a dynamic, non-equilibrium adaptation of schedule during construction. Changes in plans have the character of a return to a stable equilibrium. However, as studies show [1-9], construction (especially in the case of large projects) is often characterized by "balancing on the edge of chaos" and "butterfly effect", which necessitates periodic radical revision and adaptive changes in schedule. An overview of these studies on "dynamic" scheduling is presented below.

Benne B.C. (2005) [1] notes that architectural, engineering and construction (AEC) projects are complex organizations operating within a complex, dynamic and uncertain environment. At the same time, traditional project management is based on the old mechanistic and deterministic

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assumption that organizations and the external environment function as linear, causal systems, and

therefore predictable. Monitoring consists in identifying disturbances in the external environment in order to predict changes and develop a management plan for them, thereby maintaining the equilibrium of the project.

However, the effectiveness of traditional management strategies is very limited when managing modern project organizational structures in a complex and uncertain environment. According to complexity theory, the behavior of complex systems cannot be predicted, since even the slightest disturbances can be amplified after some time by nonlinear chains of cause-and-effect relationships that cannot be predicted. From this point of view, the organization of AEC projects is a complex adaptive system.

Herroelen, W., & Leus, R. (2005) [2] argue that the vast majority of research efforts in the field of project scheduling assume complete information about the scheduling task and a static deterministic environment in which a pre-calculated schedule will be executed. However, in the real world, project processes are subject to considerable uncertainty, which is gradually resolved during the implementation of the project. The study provides an overview of fundamental approaches to scheduling under uncertainty: reactive scheduling, stochastic scheduling, stochastic network planning GERT, fuzzy scheduling, robust (proactive) scheduling and sensitivity analysis. The potential possibilities of these approaches to the scheduling of projects under conditions of uncertainty are discussed.

The study Taylor, T., Ford, D. N., & Johnson, S. (2005) [3] examines the dynamics of the project from the perspective of the so-called "critical points". They call critical points the bifurcation points at which the project can go into an unmanageable state. The study shows how a simple, ordinary feedback structure can lead to complex dynamics of critical points, lead projects into a deteriorating mode of behavior, and lead to the collapse of the project. The basic dynamics of critical points in individual projects is described, analyzed and shown using the model. Some project management strategies have been tested near critical points.

In the study Ruiz, P. (2013) [4], a new numerical characteristic of project schedule's complexity from the standpoint of information theory was developed. This characteric is based on Shannon entropy, which is used to analyze the structural complexity of PERT networks. The idea of the study is that the higher the entropy, the more complex the project. It has been shown that schedule entropy increases with increasing time, as well as the number of links between activities. The main discovery of the study is that later risks significantly increase the entropy of the project compared to the same risks which appear earlier.

In 1990 E. Goldratt presented the so-called "Theory of Constraints" (TOC) [5], developed further in the "Critical Chain" [6]. A critical analysis of TOC is presented in the study Herroelen, W., & Leus, R. (2001) [7]. The purpose of the study was to emphasize the advantages and disadvantages of this method. The strengths and weaknesses of the TOC approach are considered from a position based on a critical analysis of the literature, as well as the authors' own experience in experimenting with commercial software products. The fundamental principles and assumptions of TOC were tested in a full factorial experiment performed on a number of reference examples. Contrary to the TOC statement, regular updating of the original schedule and critical chain at each decision point provides the best intermediate estimates of the final duration of the project and gives the shortest final duration of the project. The use of methods of "smart" scheduling and rescheduling deadlines, such as the branches-and-bounds, has a positive effect on the final duration, as well as the percentage of deviation from the optimal final duration, if the information is perfect, and the current process. Using the 50% buffer size rule can lead to a serious overestimation of the size of the project buffer. The assumption about the size of the "2-sigma" buffer is not justified. Sequential execution of critical chain activities is harmful for the final duration of the project. It is shown that the recalculation of the original schedule at each decision point has a strong positive impact on the final duration of the project.

Eden, C., Williams, T., Ackermann, F., & Howick, S. (2000) [8] argue that it is well known that small interruptions and delays can lead to serious consequences for the life of a large project, much more than can be easily attributed to their direct impact. However, the nature of these "interruptions and delays" is still not fully understood. This article discusses some of the challenges and difficulties in achieving a complete understanding. In particular, it represents the various ways in which interruptions occur, and the various consequences that can be caused by them. The article also focuses on some problems that arise when "normal" methods of analyzing complex projects can be used, for example, analyzing and evaluating changes in tasks and using network analysis. The role of dynamic feedback and the "portfolio effect" is presented, especially in relation to the acceleration of project implementation and changing labor productivity.

Bertelsen, S., & Koskela, L. (2003) [9] argue that construction projects are often very complex and dynamic in nature, and it is a well-known fact that such systems are on the border of chaos. The purpose of the study is to study construction projects balancing at the edge of chaos, and to study the forces that can make projects chaotic in the sense that the project crosses this dangerous line. The main goal of the study was to understand how a phase transition can occur and to propose an approach for understanding this risk and keeping it under control in the process of project management. The work also explores this understanding of construction projects by proposing a way to analyze its complexity and dynamics by four characteristics: project complexity, project external and internal setup, and project organization. The goal was not only to achieve a deeper understanding of the nature of projects, but also to outline a tool for analyzing and comparing the risk that the project will become chaotic. However, before revealing this main topic, the phenomenon of chaos in projects was considered through a literature review and illustrated with empirical project examples.

2. Methods

Dynamic scheduling assumes that changes are often made to the schedule during construction. In complex projects, even small changes can lead to critical consequences, so the quality of decisions on changes is of particular importance. Making such decisions is an extremely difficult task. To simplify it, special visualization methods are used - mainly Gantt chart and network diagrams. However, these methods are primarily aimed at primary planning and are not very convenient for changes in the plan, since the current schedule does not reflect previous changes and the degree of deviation of activity durations from the initial schedule. This contributes to insufficient consideration of previous changes when making decisions, which can lead to serious mistakes. The author proposed a modification of the Gantt chart, which allows to reflect the deviation of activity duration from the initial schedule, i.e. the dynamics of changes, and thereby improve the quality of decisions [10, 11]. In this modification, the bars which represent activities in the Gantt chart are replaced by stylized images of springs.

Construction schedules are often highly volatile during execution [12], especially at an operational level [3]. There are different types of changes such as increasing or decreasing activities' expected duration, interrupting, postponing the start of an activity, as well as adding new ones, e.g. rework in order to eliminate defects [3]. The need to make changes is related to impossibility or inexpediency of following the original plan [12, 13]. It might be due to changes in project requirements [14], poor execution requiring rework [3], delivery delays, etc. [15, 16]. Changes in one activity cause changes in others which are directly or indirectly related to it. In complex projects which are characterized by a large number of interrelated tasks, multiple stakeholders and high uncertainty, changes even in one activity can lead to significant ramifications for the project as a whole [3, 16]. These ramifications can be either positive (for example, reducing the duration of a critical path activity decreases the duration of the whole

project), or negative, even up to failure [12, 3]. Failure is referred here as the refusal to continue the project or significant time and/or cost overruns if the project has been still completed [3]. An example of changes' negative ramifications is work quality deterioration due to so-called "schedule pressure" [3], i.e. deadline overreduction, which is a decision often used to compensate for delays. Poor quality necessitates rework, the time lost on it is compensated again by pressure on performers, which leads to new quality problems and, consequently, the need for new corrections [3]. Thus, a "vicious cycle" occurs that can destabilize the project and lead it to collapse [3]. Of course, such a development can be prevented by increasing workforce, but such an increase faces a number of constraints, such as lack of space [18, 19]. Other negative consequences of changes are related to violation of stakeholders' own plans, which leads to inefficient resource allocation, conflicts [12], and other problems.

Thus, project management effectiveness is largely determined by the quality of decisions on rescheduling. In complex projects, making such decisions is an extremely difficult task, since it involves finding a compromise between multiple stakeholders, rational allocation of various resources, and forecasting the immediate and long-term consequences of the decision [12, 3]. The situation is exacerbated by the non-linearity of factors affecting the activities. It means that the events that are insignificant individually may lead to large and often hardly predictable consequences in the context of the whole project [3, 17]. Furthermore, it is difficult to formalize some factors, such as staff qualification and motivation, so in practice they are taken into account by managers intuitively to a certain extent.

One of the most effective approaches to facilitate decision-making is visualization. Visualization allows to present large amounts of information in a quite simple, intuitive form. There are many visualization methods used in project management [20, 21]. In scheduling, the Gantt chart and network diagrams (used in CPM, PERT, GERT methods) are the most common [22, 23].

However, these methods are mainly aimed at visualization at the project design stage, helping designers to create a process structure, allocate resources, identify critical path, etc., and are not very convenient for rescheduling. Based on the schedule created at the *n*-th change, it is impossible to find out anything about previous changes, as well as about the degree of activities durations' deviation from the initial schedule. That contributes to making decisions without taking into account previous changes. For example, if one needs to reduce the backlog, he/she may decide to increase schedule pressure, while it is already critical due to the early decisions. This can lead to project destabilization by "vicious cycle", as described in [12]. Thus, it is necessary to develop visualization methods with "accumulation", in which each new graph reflects the "trace" of previous changes and deviations from the original plan.

As such a method, the Gantt chart modification is proposed by the author, in which each activity-representing bar is replaced by the image of a spring used in mechanics (figure 1). This image is a simplified projection of a real spring on a plane parallel to its axis. This projection is a jagged polyline (the projection of a cylindrical helix - spring's geometric shape). The distance between the spring's start and end points ("axis length") is proportional to the activity's duration (t), similar to the length of a bar in the Gantt chart. Therefore, it can be denoted just as t and measured conditionally in units of time ("months", "days", etc.), implying the corresponding spatial units (e.g., "month" may mean 1 cm of "axis length"). The same applies to other spatial parameters in the chart – all of them will be conditionally expressed here in the corresponding time units. The distance between the nearest intersection points of a "spring" with its own axis ("step" x_0) is constant. It is convenient to make the step equal to a duration unit. The "teeth" of the spring (the turns of the helix in the projection) alternate staggered on the sides of the axis. The distance between the axis and the teeth' vertices (h) is constant, the projection of a vertex on the axis divides a step in half. In the original graph, the angle at the top of the teeth is 90° (figure 1a), which is meant to be perceived as equilibrium. At the first change in the graph, the

springs are "compressed" and "stretched" - a step decreases/increases in proportion to the reduction/increase in activity's duration (figure 1b). For the second change, x_0 and t_0 is assigned the values of the step and duration after the first change (respectively x_1 and t_1), the resulting step and duration is assigned the index 2. Then the procedure is repeated, in general we have an iterative process:

$$x_i = x_{i-1} \cdot \frac{t_i}{t_{i-1}}, \qquad i = 1,\ 2, \ldots \tag{1}$$

where t_i, x_i - respectively the activity duration and the step after the *i*-th change; t_0, x_0 - respectively the activity duration and the step in the initial schedule.

The spring's shape (the number of teeth, "diameter") remains the same, only axis length changes, which creates illusion of "compression" or "stretching". The decision-making manager can see which activities deviate from the original schedule and how much. This helps him/her to determine which activities should not be reduced, since they have already been significantly compressed, and which ones should be given a particular attention to due to huge delay.

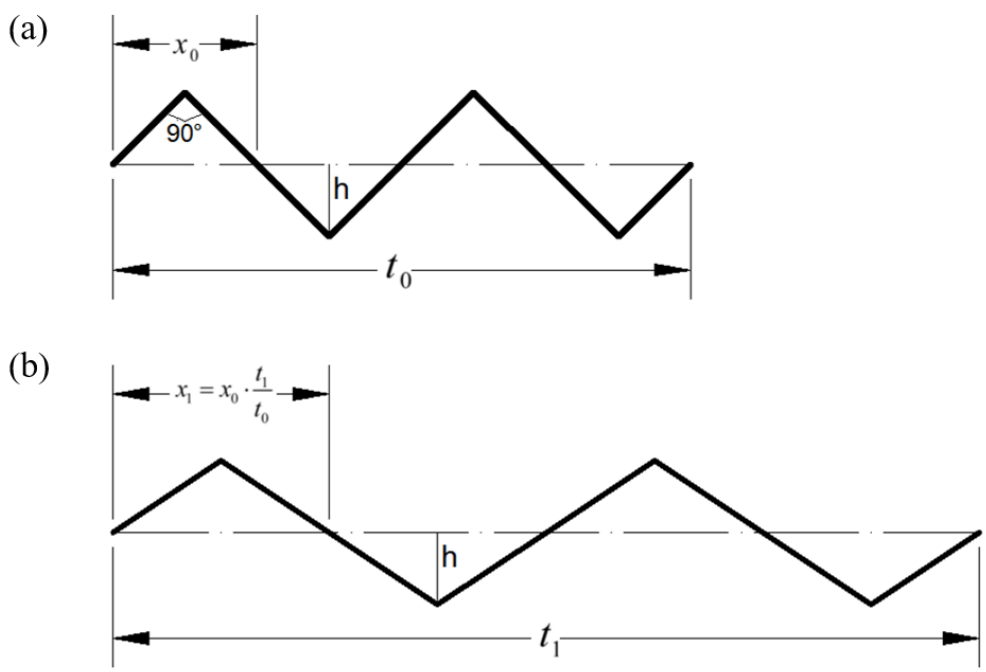

Figure 1. Activity image in the form of spring (instead of the Gantt chart's bar): a) in the initial schedule; b) after the first change.

3. Results

The following example is given in order to explain the modified Gantt chart drawing up (figure 2). The schedule consists of 5 activities. According to the initial plan (figure 2 above), Activity 1 lasting 4 months opens the project, Activities 2 (5 months) and 3 (3 months) begin

immediately after the end of Activity 1, Activity 4 (3 months) follows Activity 3, and the final Activity 5 (4 months) begins only when all the previous ones are completed. The step for all activities is assumed to be 1 month. During the Activity 1 execution, it was found that productivity had been overestimated and the expected completion of Activity 1 would not be 4, but about 6 months. That necessitates rescheduling in order to prevent the overall project deadline's disruption. The graph after the change is shown at the bottom of figure 2. To alleviate risks, it was decided to reduce the duration of the activities which follow Activity 1 directly: Activity 2 - from 5 to 4 months, Activities 3 and 4 - from 3 to 2 months. The corresponding steps after the change are (according to equation (1)): Activity 1: 1×(6/4)=1×1,5=1,5 (months); Activity 2: 1×(4/5)=1×0,8=0,8 (months); Activities 3, 4: 1×(2/3) =0,66 (months).

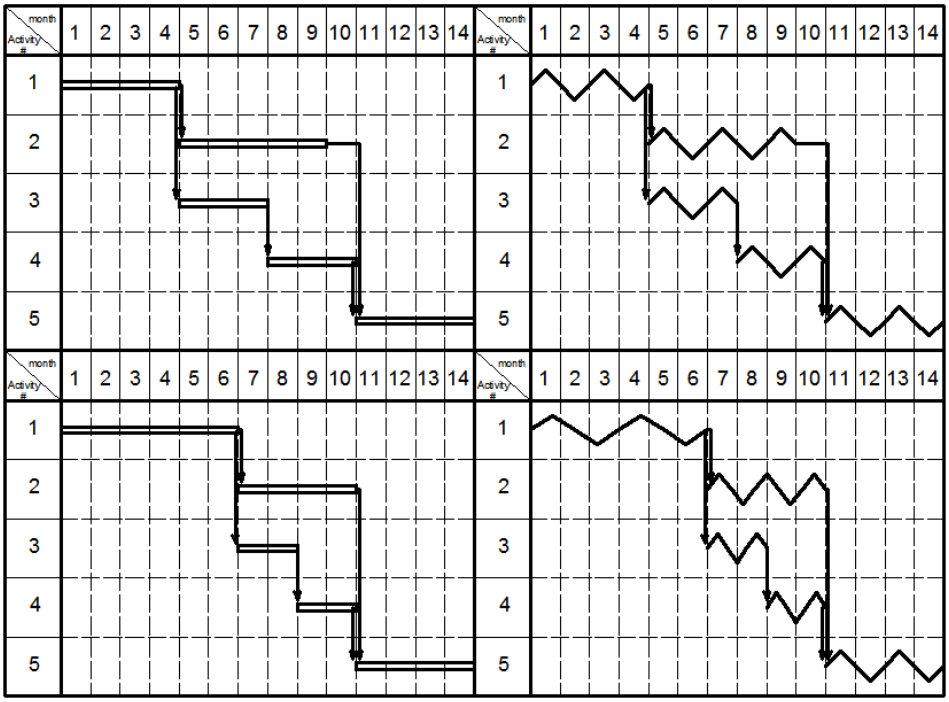

Figure 2. The example: at left – the traditional, at right – the modified Gantt chart. At the top – the original plan, at the bottom - the plan after rescheduling.

4. Discussion

If further reductions in the activity duration are necessary, it will be easy to see from the last graph (figure 2 bottom right) that Activities 3 and 4 are reduced most strongly, and it might be more rational to compress Activity 2 or even 5. Besides, comparing the graphs obtained as a result of a number of consecutive changes, one can get insight into the dynamics of activities durations' changes. In particular, it can facilitate identification of the most volatile activities (the variability of the expected activity's finish may be caused by frequent occurrence of defects). This is especially important if the similar projects are planned in the future, since studying a "history of spring fluctuation" can contribute to more accurate assessment of the activity duration and risks at the project design stage.

Worth noting that the example given is very simple. It is unlikely that making decisions on changes in such projects might cause any problem even if there is no deviations' visualization.

The proposed method focuses mainly on far more complex projects, such as nuclear power plants construction, in which the number of activities is measured in thousands. A simple example is given only for illustrative purposes.

5. Conclusion

As a result of the conducted research, it can be concluded that "dynamic" scheduling has great prospects. At the same time, the direction is not sufficiently developed in comparison with "static" approaches. The article discusses one of the possible directions for the development of "dynamic" scheduling, namely scheduling visualization techniques on the example of the "spring chart" developed by the author. As a way of further development of the technique, it is possible to indicate, first of all, its approbation on examples from real construction practice.

The main result of the study is the Gantt chart modification, which facilitates taking into account previous changes during rescheduling. The bars that represent activities in the Gantt chart are replaced with images of springs, which are “compressed” or “stretched” according to changes in the schedule. Thus, the modification can be called “spring chart”. Such presentation contributes to intuitive understanding of the activity duration’s degree of deviation from the initial schedule. This is important for deciding the duration of which activities should be changed and how much. Thus, the proposed modification of the Gantt chart can improve the quality of decision-making on rescheduling, which is especially important for complex projects where incorrect decisions may lead to critical consequences. Besides, the “spring chart” can become a convenient tool (a kind of illustration) when analyzing the "project history", which is especially important when the similar projects are planned.

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