Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 182 (2017) 33 – 41

Procedia Engineering

www.elsevier.com/locate/procedia

7th International Conference on Engineering, Project, and Production Management

Application of Critical Chain Management in Construction Projects Schedules in a Multi-Project Environment: a Case Study

Krystyna Araszkiewicz*

West Pomeranian University of Technology Szczecin, Faculty of Civil Engineering and Architecture, 30 Piastow Av., 70-311 Szczecin, Poland

Abstract

The aim of this paper is to present the results of a comparative analysis of the application of the critical chain project management and traditional scheduling established according to the critical path method for the programme of the construction of several marinas in north-western Poland. Obtained results are of a significant importance as their possible application by building contractors or investors. Besides, they might be useful for further research connected with the effective management of a set of projects.

Peer-review under responsibility of the organizing committee of EPPM2016

Keywords: critical chain; construction project; resource constrained project scheduling; multi-project environment

1. Introduction

The ability to manage multiple projects in the dynamic and competitive modern economic environment becomes a key competence which may have a significant impact on building a company's competitive advantage. Most companies in the construction industry operate in a multi-project environment, generating revenue from projects whose implementation is a result of sales activities and obtaining external orders. The subject of managing multiple projects consists in project programmes and portfolios. Projects which are implemented simultaneously yet independently of each other and share the resources necessary for completion create a project portfolio [1]. Achieving synergy and strategic objectives of an enterprise requires here a skilful overcoming of difficulties with regard to the selection of projects, corresponding company strategies, and optimisation of the use of resources by individual projects. While the distinguishing feature of the programmes is the common objective of the group of projects, the

* Corresponding author. Tel. + 4-866-413-5312.
E-mail address: Krystyna.Araszkiewicz@zut.edu.pl

1877-7058
Peer-review under responsibility of the organizing committee of EPPM2016
doi:10.1016/j.proeng.2017.03.108

achievement of which would not be possible under separate implementation of individual projects. The dominant problems in managing a programme are related to the coordination of individual elements of the schedules with the programme implementation plan [2].

One of the crucial decisions conditioning effective management of multiple projects is to determine an optimisation strategy. The deciding factor as to whether the project portfolio or programme has been designed optimally may be a particular resource, project risk or timeliness. Time is a particular type of resource. It cannot be stored, therefore in the management of individual projects as well as a portfolio of projects a lot of attention is paid to scheduling the undertakings and monitoring their implementation with regard to completion within a specified timeframe [3].

2. Research Objective and Methods

The aim of this article is to present the issue of scheduling construction undertakings implemented in a multi-project environment with the use of the critical chain method. The second objective of the article is to present the results of a comparative analysis of application of the critical chain project management (CCPM) and traditional scheduling established according to the critical path method (CPM) for the programme of the construction of several marinas in the area of north-western Poland. The research questions are: how can the implementation of the theory of constraints through the critical chain method increase the efficiency of scheduling construction undertakings in a multi-project environment.

The adopted research methods included a review of literature and case study, including analysis of contract documentation. As part of the case study, a comparative analysis of the schedules prepared in the traditional method and in line with the assumptions of the critical chain for an investment programme related to the construction of a network of ports and marinas has been carried out.

Relatively few publications have been devoted to date to the issue of multiple projects management in the construction industry. The analyses and studies in this field are related mainly to high technology industries, in particular to the fields focused on the development of new products [4]. Meanwhile, dynamic changes strengthening the multi-project phenomenon have been taking place in the economic environment of enterprises for a long time now. An individual approach and focus on client's needs as well as the pressure of capital markets on creating the enterprise's values implicate the need to increase operational efficiency, achieved mainly through the reduction of costs and the increase of effectiveness of resources use [5].

3. Background

Multiple projects management is characterized by the complexity of the issues related to planning, organizing, coordinating and controlling a set of projects simultaneously. Thiry [6] defines the management of the project portfolio as a process of analysis and allocation of resources between organizations, projects and programmes, conducted in order to achieve the organization's objectives and maximize value for stakeholders. In this dynamic process of decision-making the set of active projects is constantly reviewed and updated [7]. The three main questions that need constant verification of answers in managing a set of projects can be formulated as follows [8]:

- whether the right projects are implemented in the context of the strategic development vision
- whether the expenditure incurred on projects are strategically justified
- whether the organization has the resources necessary for the implementation of these projects.

A comprehensive multi-project environment is formed mainly by two factors: uncertainty and links between projects. The notion of uncertainty brings another factor crucial for the management of a single project or a set of projects, i.e. risk. The common feature of the management of multiple projects is the necessity to solve the conflict of resources resulting from the links between the projects. Most frequently, the critical resource are people – employees having specific qualifications [9]. The managers focus on the allocation of resources and their ongoing relocation, aiming to solve the problems at the interface of projects on a daily basis. The resource allocation syndrome as a common feature of management in a multi-project environment results primarily from inadequate planning, the indication of which is among others giving priority to projects post factum (*after-the-fact prioritisation*). Also, the schedules are prepared at the level of individual projects, not at the portfolio level [10]. The Resource Constrained Project Scheduling Problem (RCPSP) is a classic scheduling problem, the solution for which aims at minimising the makespan [3].

In a multi-project environment, management decisions connected with solving the Resource Constrained Multi-Project Scheduling Problem (RCMPSP) concern such allocation of limited projects that will allow for minimising the average delay within an individual project or shorten the completion period of an entire set of projects [11]. The methods aiming to solve resource allocation problems classified as N-difficult include precise and heuristic methods, where the former are used with regard to simple scheduling issues, whereas the second group is suitable for solving complex problems, including in a multi-project environment. In practice, due to a significant effort required when building a network, heuristic methods for calculation purposes are used to a limited extent; algorithms based on the priority principle are more frequently used [9, 11]. An ordered, comprehensive attempt to solve problems occurring in the management of multiple projects consists in the critical chain method based on the assumptions of E. Goldratt's theory of constraints. The starting point of this method is the identification of constraints and it also assumes the need to specify not only physical constraints (of the critical chain) but also procedural constraints, which are usually of a behavioural nature and arise from fixed patterns of employees' behaviour [12]. A constraint is a resource which prevents a better achievement of the objective for which the system was designed. On the level of the system, a constraint can be the insufficient availability of financial resources or multitasking [13, 14].

The period of time in which a project must be completed is considered as one of the main constraints, which is due to three main reasons [15]:

- a delay in project implementation has negative consequences regarding cash flow, related primarily to the increase of general costs (overhead costs)
- a delay in project implementation results also in a very high increase of cost contingency
- the expectations of stakeholders are modified and in a situation of extending completion times of the project or project portfolios there may occur expectations to change the scope of the said projects, change the technology of implementation of project tasks or change the functionality of the subject of project activities.

In construction undertakings there is a clear correlation between the project completion time and its profitability. Exceeding the directive project deadline has negative financial consequences, such as for example a delay in achieving the intended benefits, postponing profit, and frequently loss of profit and share in the market. The consequences of a delay in an investment and construction project may be significantly greater than exceeding the budget alone.

3.1. Schedule pressure

The perception of time as a key constraint is connected with schedule pressure, defined by Yaghootkar and Gil [16] as a gap between the assumptions of the project manager concerning the time necessary to complete the project, with the allocation of resources planned at the beginning of the project, and the actual number of days necessary for the completion of all activities under the project. Frequent, unplanned transfer of resources of a specialist nature between the projects which are aimed to remedy the situation regarding project delays, on a fire extinguishing basis, are some of the reasons for scheduling pressure in a multi-project environment. Lack of a thorough analysis at the planning phase, abandonment by the project team at this phase of activities related to risk analysis and assessment with indication of a strategy for mitigation of threats, may lead to a situation of continuous fire extinguishing in next projects from the portfolio, which will have a negative impact on the organisation [16]. Multitasking related to the necessity to organise work in a multi-project environment in which multiple projects sharing resources are implemented simultaneously and the limited availability of "key" resources necessitates competition between projects for access to those resources. Overburdened resources migrate between projects in reply to the last, "loudest" request, trying to satisfy as many clients as possible. On the other hand, well-planned simultaneous performance of tasks may be a significant element of improvement of effectiveness of activity, reducing project duration and enabling better use of resources. Therefore, the issue of multitasking should be approached carefully, considering the realities of a given project portfolio or programme and accordingly determining its optimal level [12].

3.2. Critical chain in multi-project environment

Completion of a task in a project is determined by the completion of the preceding tasks and the availability of appropriate resources. The key constraint which impedes the achievement of the assumed objective, being the maximum reduction of the project completion time, is the duration of the activities necessary to perform the tasks of the critical path. In the traditional approach, when determining the critical path only logical relationships between the tasks are considered, i.e. the cause and effect sequence of activities. A key aspect of the alternative method proposed by Goldratt is the replacement of the critical path with the critical chain. When determining the critical chain both logical relationships between the tasks and the resource dependencies (availability of the resources necessary to perform the task at a given time) are considered [12, 25, 26]. The estimation of duration of individual tasks in a project is carried out with the assumption that in order to increase the probability of performance of tasks within the assumed deadlines, when planning projects a common practice is to overestimate the duration of individual activities. This way, in the traditional method of the critical path reserves included in the estimation of time necessary to perform each task are created. In the critical chain method those reserves are eliminated by determining the most probable time, which in the case of beta distribution is on average 50% shorter than the time estimated with probability 90% [17]. For safety in terms of timeliness, three buffers are introduced to a schedule: a project buffer, feeding buffer, and resource buffer. Whereas it is assumed that the introduced buffers and shorter duration of tasks will not result in a change of the course of the critical path [18].

A project buffer is introduced at the end of the critical chain. The aim of this buffer is to allow for meeting the planned project completion deadline under normal uncertainty connected with the duration of individual tasks. The critical chain method assumes that the size of the project buffer constitutes half of the sum of individual reserves in the critical chain, while the way of determining the size of this buffer proposed in this method is subject to doubt and discussion [12, 19]. Feeding buffers are introduced in places in which other tasks connect with the critical chain. Their role is to protect the critical tasks against the impact of delays on feeding paths, enabling also earlier commencement of activities in the critical chain. Resource buffers are included in the schedule in places where the tasks in the critical path require a different type of resource than the previous task. They do not have a time dimension and their role is to provide the allocation of an appropriate renewable resource for the performance of a given activity from the critical chain [19]. Many publications have been devoted to the issue of determining the sizes of buffers. They include numerous proposals modifying the assumption of the critical chain method and the methods for calculating the buffers [12, 18, 19, 21]. The proposed methods for calculating buffer sizes and creating a schedule are to a large extent related to the attempt to ensure stability of commencement dates of individual activities, which in literature sources is called solution robustness [19, 20].

In a multi-project environment, the critical chain multi – project management method (CCMPM) is used in scheduling the projects comprising a portfolio, including the following stages [5]:

- giving priorities to projects, in line with the organisation's strategy
- developing schedules for individual projects with the use of the critical chain method
- identifying the critical resource
- summarising critical resource tasks
- ordering the projects on a timeline so that they are carried out in accordance with the given priorities with the shortest possible stoppage in the operation of the critical resource which sets the pace of implementation, hence the term drum resource
- introducing capacity constraint buffers.

The aim of the buffer for the drum resource is the protection of the next project's commencement date against the impact of delay in the preceding project. Its size is determined according to the principles of uncertainty buffering. At the final stage a resource schedule is generated, which includes the duration of the drum resource tasks execution and a list of tasks of other resources.

4. Critical chain in planning construction programmes and portfolios of construction projects

A significant aspect of applying the constraints theory is the transfer of changeability in performing the tasks under projects to buffers, which facilitates to a large extent the management of project uncertainty and risk [5]. The most common factors generating a high risk of investment undertakings in the construction industry are: the heterogenic nature and lack of seriality of the production process (whereas it does not include the production of materials and construction products), implementation of projects in a complex environment burdened with great uncertainty as to implementation conditions, very dynamic, involvement of many stakeholders whose objectives are frequently not consistent or complementary, dependency on natural conditions, including primarily regarding climate, long preparatory period, division of responsibilities between many process participants [21]. The application of the critical chain method in managing multiple investment and construction projects requires a reliable estimation of tasks duration as to enable efficient functioning of buffers and completion of the projects as quickly as possible [22].

Lau E. and Kong J. [23] state that the identification of the constraints as the first step to apply TOC in project management enables to make better managerial decision and achieve higher performance in construction project management. Based on literature review the constraints have been classified into five categories: economic constraints, legal constraints, environmental constraints, technical constraints, and social constraints. The identification of constraints helps projects managers not only to understand the nature of those constraints but also enables them to predict the time of occurrence of a given constraint with respect to the stages in the life cycle of a construction project. Economic constraints and legal and environmental considerations occur primarily at the stage of project conceptualization and planning, affecting the scope and content of the construction project. During the project execution stage and subsequently the operation stage it is expected that technical and social constraints will occur. Reliable forecasting of constraints facilitates the planning and allocation of resources, the project manager can assess whether a given constraint is temporary or whether it will affect the implementation process throughout the project's life cycle [23]. Estimating buffer sizes and balancing the resources are the two main scheduling challenges of construction projects using the critical chain method. Buffers play a key role, whereas it is demonstrated that 50% of estimates is too arbitrary and therefore their use in planning construction projects is not appropriate [23, 24]. The sizes of buffers may be too large, which will result in resources being wasted or the project not being sufficiently resistant to the influence of uncertainty and risk. Hence the numerous publications proposing modified ways of estimating the amount of resources. Another area of challenges for a project manager applying the CCPM method is planning of resources. When planning resources in a multi-project environment, critical chain method recommends staggering the release of projects around a key resource that acts as a virtual drum. This is used to ensure flow and avoid too many open projects that result in excessive multitasking and missed due dates.

5. Case study

The issue of scheduling construction projects implemented in a multi-project environment with the use of the critical chain method has been analysed under a case study of the construction programme of marinas infrastructure, whose aim was to create a network of functionally linked ports and marinas.

According to the definition proposed by the PMI a programme is a group of projects that are related, managed and coordinated so as to achieve the benefits impossible to achieve in the case of individual implementation and management of each project separately. An important feature of the programme in the context of multi-project environment is centralized, coordinated management, focused on objectives and strategic benefits of the programme as a whole [1]. Managing the programme as a set of projects, includes identification and managing the project connections, prioritization of the use of resources and reduction of the total effort related to managing all of the actions constituting the programme.

The analysed programme of building a sailing route, has met the conditions resulting from this definition. The scope of the programme included the development and reconstruction of 4 existing marinas and construction of 6 new ones. Each project could be executed individually. However, the goal of the programme has been to build a supraregional tourist route, unique on a national scale, and thus an economic development of the polish Baltic seaside region through the development of the national and foreign water tourism. Achieving this goal was possible only as a result of executing a comprehensive programme, which has been created by financially and organizationally connected infrastructural projects. Their connection manifested itself also in the manner of managing the programme. The analysed programme included projects owned by ten investors of different legal status (associations, local governments, municipal companies), who, for the purposes of implementation of the programme, have created a common organisational structure with characteristics similar to a consortium. A partnership agreement indicating the programme leader has been concluded for the purposes of programme implementation. A significant determinant of the programme consisted in the implementation of individual investment and construction projects in nine different places located at a distance of a dozen or so or several dozen kilometres from each other. Therefore, it was vital to ensure an appropriate structure of programme management. Within the organisational structure of the leader a common programme management office (PMO) has been created, with the purpose of coordinating the projects comprising the programme. There were only four persons working at the PMO – programme manager, technical coordinator, finance specialist, and promotion and administration specialist.

Investment outlays of over PLN 98 million included the costs of drawing up design documentation, carrying out construction works, investor supervision, preparing application documents, drawing up mandatory audits and conducting promotional activities and activities regarding project management. A part of these costs was subject to refund under the subsidies from EU funds. Due to financing from external sources, an important responsibility of the PMO was the control of compliance of programme implementation with the co-financing agreement, including compliance with the assumed completion deadlines of individual investments and the entire programme. All examined investments comprising the programme were implemented according to the traditional model in which the investor – the ordering party provides the construction documentation, while the contractor is involved solely in the performance of construction works. Preparatory works (design and technical documentation) regarding individual investment projects under the programme were carried out individually by investors and were initiated in 2008. Whereas public procurement procedures for the works and implementation of investment projects forming the programme were planned for 2011-2013. As preparation of the programme, an analysis and quality assessment of risk for individual projects and for the whole programme was conducted.

Due to the multitude of tasks performed under the programme, the key identified risk was untimely investment completion. The specific technical nature of the programme, under which some of the works were planned for implementation in harbour basins, was significant for the assessment of this risk. The course of these works strongly depended on weather conditions. The risk of postponing the deadline for performance of works was assessed by determining a relatively high probability of occurrence and significant influence on the programme. It was predicted that this risk will be subject to systematic monitoring by the PMO. To minimise the occurrence of a time risk, the draft agreements with subcontractors provided for liquidated damages for failure to perform the works in line with the adopted schedule. Also, in order to prevent the occurrence of this risk, it was agreed that the tasks of the engineer's team supervising the implementation of individual investments under investor supervision included among others the control of compliance of performance of individual investments with material and financial schedules of individual contracts and the material and financial schedule of the programme. At the programme planning stage, schedules of projects and programme were prepared in the traditional method CPM with the use of MS Project, including the specific technical nature of individual investment undertakings, considering also the climate conditions on the coast, i.e. in the location of most of the investments.

For the purposes of this study, the schedule prepared for the programme was modified in accordance with the assumptions of the critical chain method. In line with this method, the first step should be giving priorities to projects, corresponding to the strategy of the organisation's development. In the examined case, each undertaking was important in terms of programme objectives, as the achievement of the assumed result, i.e. a consistent infrastructure of a nautical tourism route, was determined by the construction and modernisation of all facilities planned under the programme. However, it was assumed that it is important for the effectiveness of the programme to keep the planned distance between individual units of the tourist route, because it was determined considering the safety of sailing. Therefore, priority was given to two undertakings, whose delay or failure to complete would break the continuity of the route and result in increasing the distance between ports beyond the adopted one according to the safety criterion. Subsequently, the schedules of 10 individual investment projects under the programme were modified in accordance with the procedure algorithm adopted in the CCPM (Table 1).

Table 1. Modification of projects schedules.

Project	Duration of project CPM (*days*)	Duration of project CCPM (*days*)	Project buffer size (*days*)
Project 1	181	117	39
Project 2	100	88.5	29
Project 3	496	413	135
Project 4	320	240	80
Project 5	327	256	85.5
Project 6	375	279	93
Project 7	310	232.5	77.5
Project 8	102	75	26
Project 9	275	208.5	69.5
Project 10	240	172	58

In order to calculate the size of buffers on the basis of the normal distribution of duration of tasks covered by the scope of individual projects it was assumed that the adopted duration of activities in the initial schedule was determined with 0.9 ($t_{0.9}$) probability. The duration of tasks with e.g. 0.5 ($t_{0.5}$) probability was estimated as reduced by 50% of the initial value. Based on the adopted estimates of task duration and the probability of completion within the adopted deadline and assuming a normal distribution of task duration, calculations of optimum task duration were carried out and changes to individual schedules were made. Due to the limitations of method for calculating the buffer size of the project in schedules of construction works, a technique proposed in literature was used which is based on determining the buffer size using the Finish-Start relationship with presence of both positive and negative delays in these relationships [27].

The next step was to identify the critical resource. A list of tasks performed by the critical resource was also developed. In the area of construction works, the equipment necessary to carry out dredging works on water proved to be the critical resource. Planning of works requiring the use of this equipment entailed with additional complication that resulted from environmental factors causing mandatory time limit on carrying out works on water except during water birds breeding period. The second type of critical resource was the team of inspectors from investor's supervision. According to the programme, works on individual projects could be carried out by different contractors, and investor's supervision was planned under a single contract concluded by the project leader to ensure good coordination on supervision of the whole programme. Accordingly, the next stage of the analysis focused on the attempt of setting projects composing the programme in such a way, that dredging works would involve critical resources, i.e. the equipment for dredging and supervision of the hydrotechnical works inspector. Then, capacity constraint buffers were implemented for protecting due dates for starting the projects, in which it was necessary to use critical resources. Detailed results, discussion on the list of critical resources and network diagram of the examined programme with buffers introduced with use of CCMPM method are the subject of a separate, more comprehensive study.

According to information obtained from the statistics of MS Project, planned duration of implementing the entire programme including the buffers was 586 days. Planned implementation time of a complete programme with traditional approach of estimating duration of individual projects was 794 days. The difference is 208 days. It means that planning of the investment programme in this case with the use of critical chain method could help to speed up the date of its completion.

Analysis of investment programme schedule described in the article was carried out *ex post*, after the successful implementation of all projects under the programme scheduled using the classical method of critical path. The actual time of conducting the programme has been over four years, however an important factor for such a long duration has been the need to conduct archaeological researches in the course of one of the projects, which took over a year. The subject of this article is however the usage of the CCMPM method at the stage of programme planning, thus the issue of factors influencing the execution of the programme has not been discussed in detail. The use of critical chain method in the analysed case could result in tangible benefits for project participants, resulting from shorter implementation time, better coordination of resources and stronger motivation for programme participants to finish works before deadline. The condition for achieving the latter effect, however, is the use of CCMPM method by all contractors of individual investment projects that are within the scope of the programme, which could be a significant barrier for implementation based on the assumptions of method presented in the article, both at the planning stage as well as in the next phase associated with monitoring of programme implementation.

6. Conclusion

Managing projects in multi-project environment are mainly activities focused on synchronizing the use of critical resources while timing projects. At the level of the programme or projects portfolio the critical chain method in projects planning proves its usefulness primarily due to a systematic approach to the identification and planning of the use of critical resources in time while taking into account the strategic priorities of project organization.

Barriers resulting from construction practice for using CCMPM in managing of construction projects portfolios are mainly connected with decision-making limitations concerning due dates of starting the projects that in construction companies are carried out as part of the stock of orders for which investors determine the time frames in individual contracts for construction works. In the case study, a similar barrier stemmed from the conditions related to external financing – financing agreement stipulated the necessity of executing individual projects included in the programme in accordance with schedule, which is an integral part of this agreement. The event of default could result in funding loss. In contrast, if the condition of proper programme implementation would be the deadline for programme completion as a whole, the planning based on CCMPM would allow flexible scheduling of individual projects and their movement within the limits designated by capacity constraint buffers. In this way, from the perspective of portfolio, management would be improved first and foremost with a contract for investor's supervision and reduction of negative multitasking of critical resources. To verify the effectiveness of the use of CCMPM in managing multiple construction projects, it is advisable to conduct further analysis, mainly from the perspective of projects portfolio carried out within a specified time by construction company, on the basis of a set of contracts and schedules of various structures.

Acknowledgements

Ministry of Science and Higher Education
Republic of Poland

7th International Conference on Engineering, Project, and Production Management (EPPM2016) was financed in the framework of the contract no. 712/P-DUN/2016 by the Ministry of Science and Higher Education from the funds earmarked for the public understanding of science initiatives.

7th International Conference on Engineering, Project, and Production Management (EPPM2016) finansowana w ramach umowy 712/P-DUN/2016 ze środków Ministra Nauki i Szkolnictwa Wyższego przeznaczonych na działalność upowszechniającą naukę.

ARiMR

7th International Conference on Engineering, Project, and Production Management (EPPM2016) was co-organised by the Agency for Restructuring and Modernisation of Agriculture (Poland).

References

[1] *The Standard for Portfolio Management*. Project Management Institute Inc.; 2013.

[2] Trocki M. *Nowoczesne zarządzanie projektami* [Modern project management]. Warszawa: PWE; 2012.

[3] Marcińczyk B, Skołud B. Harmonogramowanie z ograniczeniami projektów współbieżnych [Resource – constrained multi project scheduling]. In: Knosala R, editor. *Innowacje w zarządzaniu i inżynierii produkcji* [Innovations in managementand production engineering]. Opole: Oficyna Wyd. PTZP; 2012, p. 421–432.

[4] Hashim NI, Chileshe N, Baroudi B. Management challenges within mutiple project environments: lessons for developing countries. *Australasian J of Construction Economics and Building Conference Series* 2012;1(2):21–31.

[5] Sonta-Drączkowska E. *Zarządzanie wieloma projektami* [Multi project management]. Warszawa: PWE; 2012.

[6] Thiry M. Managing Portfolios of Projects. In: Morris P, Pinto J, editors. *Gower Handbook of Project Management*, Aldershot: Gower Publishing; 2006.

[7] Martinsuo M, Lehtonen P. Role of Single-project Management in Achieving Portfolio Management Efficiency. *Int Journal of Project Management* 2007;25:56–65.

[8] Kozarkiewicz A. *Zarządzanie portfelami projektów* [Project portfolio management]. Warszawa: Wyd. Prof. PWN; 2012.
[9] Ponsteen A, Kusters RJ. Classification of Human and Automated Resource Allocation Approaches in Multi-Project Management. *Proceedia – Social and Behavioral Sciences* 2015;194:165–173.
[10] Engwall M, Jerbrandt A. The resource allocation syndrome: the prime challenge of multi – project management? *Int Journal of Project Management* 2003;21:403–409.
[11] Browning TR, Yassine AA. Resource-constrained multi-project scheduling: Priority rule performance revisited. *Int Journal of Production Economics* 2010;126(2):212–228.
[12] Bednarz L. Planowanie zadań i zasobów w projektach logistycznych metodą łańcucha krytycznego [Scheduling of tasks and resources in logistics projects with use of critical chain method]. In: *Proceedings of XII Conference of Computer Integrated Management*, PTZP Zakopane; 2009.
[13] Simatupang TM, Wright AC, Sridharan R. Applying the theory of constraints to supply chain collaboration. Supply Chain Management. *An International Journal* 2004;9(1):57–70.
[14] Adamczak M, Cyplik P, Hadaś Ł. Integracja narzędzi teorii ograniczeń jako innowacyjny model zarządzania przedsiębiorstwem z branży inżynierskiej – case study [Integrating the theory of constraints as an enterprise management innovative model in engineering industry – case study]. *Contemporary Management Quarterly* 2011;3:147–157.
[15] Steyn H. An investigation into the fundamentals of critical chain project scheduling. *Int. Journal of Project Management* 2001;19(6):363–369.
[16] Yaghootkar K, Gil N. The effects of schedule – driven project management in multi – project environment. *Int Journal of Project Management* 2012;30:127–140.
[17] Leach LP. *Lean Project Management: Eight Principles for Success*. Boise: South Pegasus Way; 2005.
[18] Połoński M, Pruszyński K. Wyznaczanie wielkości buforów czasu i terminu zakończenia przedsięwzięcia w harmonogramach budowlanych [Setting buffer sizes and a completion date for projects in constructional schedules]. *Scientific Papers of the Institute of Civil Engineering Technical University of Wroclaw (90), Studies and Materials* 2008;20:289–297.
[19] Kulejewski J, Zawistowski J. Metoda symulacyjna wyznaczania wielkości buforów stabilizujących harmonogramy budowlane [Time buffer size simulation stabilizing construction schedules]. *Civil and Environmental Engineering* 2011;2:563–572.
[20] Van de Vonder S, Demeulemeester E, Herroelen W, Leus R. The trade – off between stability and makespan in resource – constrained project scheduling. *Int. Journal of Production Research* 2006;44(2):215–236.
[21] Azevedo de RC, Ensslin L, Jungles AE. A review of risk management in construction: opportunities for improvement. *Modern Economy* 2014;5(4):367–383.
[22] Yang YB. Applying the Theory of Constraints to Construction Scheduling. *Proceedings of II Int. Structural Engineering and Construction Conference (ISEC 02)* 2003:175–180.
[23] Lau E, Kong J. Identification of constraints in construction projects to improve performance. *Proceedings of the Joint Conference on Construction, Culture, Innovation and Management* 2006:655-663.
[24] Ma G, Wang A, Li N, Gu L, Ai Q. Improved Critical Chain Project Management Framework for Scheduling Construction Projects. *Journal of Construction Engineering and Management* 2014;140(12):04014055.
[25] Mirzaei M, Mabin VJ. Exploring constraints in projects: A construction industry case study, https://secure.orsnz.org.nz/conf48/program/Papers/nzsaorsnz2014_paper_24.pdf (retrieved 31.05.2016).
[26] Goldratt EM. *Łańcuch krytyczny. Projekty na czas* [Critical Chain]. Warszawa: MINT Books; 2009.
[27] Polonski M. Obliczanie czasu bufora projektu w harmonogramach jednopunktowych z ujemną zwłoką na relacjach typu ZR między zadaniami [How to calculate project buffer time in PDM diagram with negative lag in FS relationship types between tasks]. *Scientific Review – Engineering and Environmental Sciences* 2011;53:163–173.