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A Model-Based Hybrid System for Human Resource Allocation in Multi-Project Management

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Abstract. Multi-project management (MPM) effectively handles project-based organizations that use multi-skilled shared resources to execute projects, which is crucial for engineering teamwork and transdisciplinary research. Hence, allocating appropriate resources to projects is a significant challenge. Furthermore, projects are often executed in dynamic contexts with various sources of uncertainty, necessitating resource reallocation and rescheduling, which might influence other projects due to interdependencies. While mathematical approaches can help with low complexity problems or in a relatively static environment, they have limitations in characterizing interrelationships in multi-project settings and adapting to dynamic change. Considering these problems, we propose a model-based hybrid simulation system comprising system dynamics (SD) and agent-based simulation (ABS). SD can refine the complexity of uncertainty, while ABS provides decision-making support for dynamic changes. ABS models both projects and resources as agents, whereas SD reproduces the cause-and-effect relationship between project activities. Projects require resources to accomplish their scheduled work, while resources provide their skills and staffing. The outcome helps get insights into the impact of dynamic changes on allocation to the project execution process. The system is used as a decision-support tool for evaluating and obtaining feasible resource allocation solutions considering dependencies, uncertain occurrences, and resource constraints. Another intention is to motivate a transdisciplinary-enabling framework to support the systematic integration of knowledge with stakeholders.

Keywords. resource allocation, multi-project management (MPM), hybrid simulation model, system dynamics (SD), agent-based simulation (ABS), decision-support, transdisciplinary engineering research

Introduction

Multi-project management (MPM) has become a prominent practice in project-based organizations in recent years. Today's project management must consider the interdependencies of multiple concurrent projects of diverse sizes, priorities, resource requirements from a shared resource pool, and progress levels [1][2]. An organization's capacity to manage this level of complexity determines its success or failure. As a result, understanding the process of addressing these aspects is critical for controlling and supporting multi-project management [3]. The efficient execution of multiple projects, frequently from diverse areas of activity, allows the organization to grow rapidly. In a multi-project environment, different human resources work together, whether they

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belong to the same department or another department. Hence resources are adhered to with different skills. In this case, allocating appropriate resources to the projects in a multi-project environment is complex. There are several techniques available to solve a resource-constrained problem in MPM optimally. However, these optimal methods become computationally intractable when the projects become large. Therefore, researchers have created a range of heuristics to deal with computational complexity. The main aim of these heuristics is to schedule the projects as soon as possible, and each of them is usually appropriate only for one specific type of problem. These methods focus on deterministic task duration, and their effectiveness is often not consistent with the type of problem [4][5]. However, when the problem of multi-project management with shared resources is concerned, these methods are complicated even in the case of a moderate number of tasks [3]. On the contrary, simulation modeling has become one of the most popular tools for analyzing complex systems. The popularity of simulation modeling is due to its flexibility, ability to model systems more precisely, and ability to model systems' time dynamic behavior. Furthermore, simulation models are widely used to test solutions in a virtual environment before adopting them in a real-world scenario [5][6]. In addition, the hybrid modeling and simulation approaches have proven to be effective in solving a wide range of problems [6], and they improved and enhanced the decision-making process [7]. So far, however, little research has been done considering this aspect [6]. As a result, comparative studies of resource allocation in multi-project settings from various contexts are required. This paper gives a contribution to such systematic based analysis by addressing the following two research questions:

RQ1. How should the configuration of resources be changed to complete the set of projects on schedule and on time in the absence of required resources?

RQ2. How should the configuration of resources be changed to complete the set of projects on schedule and on time when the suitable resource is unavailable?

We developed a hybrid simulation model using the system dynamics (SD) and agent-based simulation (ABS) tools. SD can refine the complexity of uncertainty [2][8], and ABS can provide decision support for dynamic changes [6]. As a result, combining SD and ABS approaches can assist overcome challenges. Furthermore, they will help improve the decision-making process on resource allocation in MPE, complementing one technique with another. Despite various applications of individual SD and ABS models to MPE, there has been limited integration of SD and ABS [9]. However, SD and ABS are two useful techniques for strategy formulation that have both demonstrated their ability to help with MPM issues. This study describes the synergistic power of combining these two approaches as a useful tool for project managers to modify the way they think and, as a result, make better use of available information.

The remaining paper is organized as follows: The 1st section outlines the current research on our issue. In part 2, we spoke about problem formulation. In section 3, the proposed technique for this study is presented. Section 4 goes over the results analysis, followed by a discussion in section 5. Finally, section 6 concludes with limitations.

1. Literature review

1.1. The complexity of managing multi-project environments

Project-based organizations' organizational design, in which many processes are arranged as simultaneous or sequential projects, is typically complex and challenging to manage [9][10][11]. When the complexity of managing, directing, and organizing a project-based organization is disclosed, a greater emphasis is placed on time and activity planning to facilitate the coordination of scarce resources within tight time constraints. Aware of this, several works argue that project-based organizations perform poorly in managing multi-project organizations and recommend that firms set up matrix-based structures to ensure project managers negotiate project priorities and resource allocation [12][13]. However, the authors acknowledge that this is easier said than done, particularly if many concurrent initiatives push the organization's resource capacity to potentially excessive levels. Significant progress has recently been made in developing acceptable methodologies for scheduling, resource leveling, and aggregate resource planning [14][15][16]. However, multi-project management remains difficult since these methods are based on a rationalistic decision-making paradigm.

1.2. Resource allocation in a multi-project environment

A multi-project environment necessitates a dynamic and efficient resource allocation method and a practical set of project delivery timetables, especially when resources must be switched during active projects [17]. Furthermore, project managers face challenges in allocating and distributing resources when they use resources from a shared resource pool and have interdependencies among projects [14][15]. Several MPM-related studies have developed and addressed resource allocation strategies. Considering uncertainty, a bottom-up strategy for resource allocation has been defined to minimize time by Zulkepli et al. [7], Khatun et al. [8]. Furthermore, a decision support system has been created to alleviate resource rivalry in autonomous local decisions by Khatun et al. [18].

1.3. Integrated approach for resource allocation in multi-project management

The hybrid project portfolio selection technique established by Archer and Ghasemzadeh [19] is based on a trade-off between quantitative and qualitative measures of interest. Dey [14] solved the integrated project evaluation and selection problem using the multiple-attribute decision-making (MCDM) method. Alvanchi, Lee, and Abourizk [10] investigated mutual influences on system performance using a system dynamics modeling approach for building operations. For this purpose, an integrated discrete event simulation (DES) and system dynamics model was presented. The efficacy of the proposed integrated simulation modeling framework was tested using a real-world building project. Pajares and López [11] contributed to the field by proposing a hybrid simulation modeling technique that combines SD and DES models to examine operational aspects impacting construction project performance. This novel technique has several practical implications. The key benefit is that the project manager can use the proposed technique to model specific and holistic elements of a large project and assess many related variables influencing construction activities.

2. Problem Formulation

In a multi-project environment, a set of projects are developed simultaneously where the start time of the projects can be similar, or they can start with a gap upon arrival. For the current analysis, the problem has been described as follows.

i. The problem consists of a set of $M\{i=1,\ldots, M\}$ projects that are to be developed
ii. Project i consists of N_i tasks with task
iii. There is a set of R $(r=1,\ldots., R)$ types of resources shared by all the projects. Resource r is available in constant amount R_{rt} in each time slot t $(t=1,\ldots T)$. The entire resource demand is less than or equal to the available resources.
iv. The first project in a multi-project instance may arrive at $t_{ri} >= 0$, while the other projects have various arrival times after the first project.
v. Task i could start when all its predecessors are completed.

In our defined problem, the objective is to complete all the projects as soon as possible. Each project has an agent to respond to any issues during the execution. A project consists of several to tens of tasks that need to be completed on one of several compatible facilities. In our problem-solving approach, to cope with complicated constraints to both facilities and tasks, which are explained in the following.

- **Resource constraints:** Two types of resource constrain are considered: 1) compatibility (multi-skilled): each facility can handle certain task types; 2) capacity (sufficiency): one facility can only accommodate one task at a period, i.e., a facility can be considered as a renewable resource with unary capacity in each time slot.

3. Research methodology

This section proposed an integrated simulation system as a decision support tool for resource allocation. Figure 1 shows the overview of the proposed methodology.

As shown in Figure 1, while developing the model, project size with context, required resources for each project, dependency among tasks and projects, and resource diversity are considered essential inputs during simulation. These input parameters will be used to obtain project performance under uncertainty, resource allocation strategy, and scheduling plan.

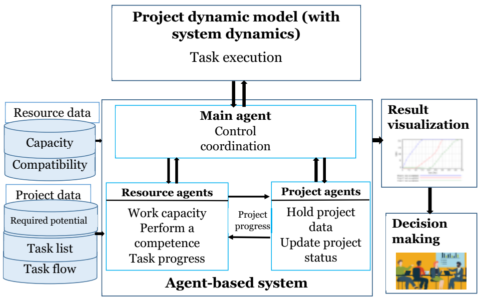

Figure 1. Overview of the methodology.

SD is used during model development to develop a project dynamic model for each concurrent project where the cause and effect of project activities are being conducted. Since resources are needed to be shared in a multi-project environment, ABS is used to make global decisions for resource allocation to each project based on the project priority and resource requirements and skills. The integrated model has been developed using AnyLogic software. A part of the developed model has shown in Figure 2.

3.1. Model building

3.1.1. Project dynamic model (with SD)

A set of projects 1, 2, …, N are to be planned to execute in a multi-project environment. The multi-project management is dynamic in nature, incorporating feedback processing and control within an organization. Besides the technical factors, the project development involves people and environments in the feedback loops. Hence, much feedback control is indirect, unplanned, or even unconscious. Since the feedback mechanisms are non-deterministic in nature, modeling or simulation must replace the analytical tools of control theory, and SD is considered appropriate for the investigation [7]. To act with the dynamic behavior of the projects, each project has its dynamic model developed in SD to simulate the project's cause and effect. The SD simulation simulates the cause and effect of resource skill and productivity to define resource performance. When the project's respective operation is started, the project agent and resource agent communicate with the project dynamic model through the main agent. Any changes in percent project completion, efficiency, schedule pressure, or arriving new projects that result in a scheduled shift will be sent back to the agents for resource allocation decisions.

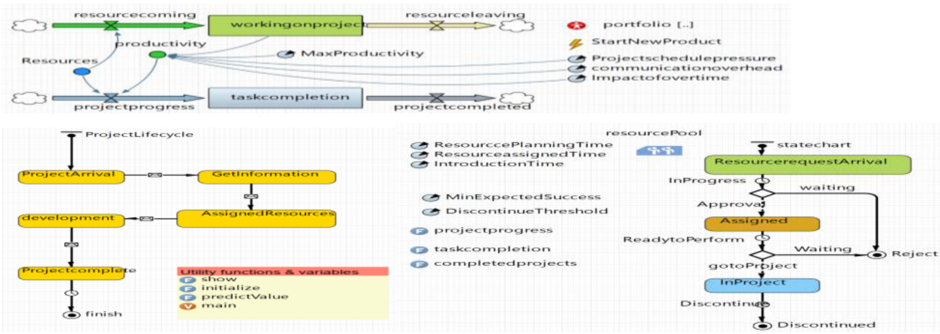

Figure 2. A part of the hybrid model developed in AnyLogic.

3.1.2. Agent model (with ABS)

An agent-based mechanism has been designed to allocate the resources to the projects at a decision point. The agent model will manage project activity sequencing and resource distribution. As shown in figure 1, three types of agents are considered: (1) project agent, (2) resource agent, and (3) main agent. Communication is an essential part of agent-based simulation to achieve its desired functionality. Each PA communicates with the RA and MA and vice-versa. Each agent's working process is outlined here.

Project Agent (PA): A project agent is a person who is assigned to a project and is in charge of its scheduling. A PA schedules related projects independently of prioritization limitations and the availability of the resources. Each PA has its scheduling component, referred to as the scheduler. The PAs compete for essential resources. The procedure carried out by RA is as follows:

Step 1.1 Send overall average resource requirement Avg_D_{gi} of active projects to RA

Step 1.2 After triggering the process, receives a message from RA

Step 1.3 Send resource free up window (RFW) in the current time to RA

Step 1.4 Receive resource availability information (RFI) from RA

Step 1.5 Receive activity performance information from the project dynamic model through MA

Step 1.6 Schedules activity accordingly and update the free resource availability matrix

Step 1.7 Gets updated resource availability information from RA

Step 1.8 "STOP"/deregister if all activities completed

Resource Agent (RA): A resource agent (RA) depicts a resource manager in charge of all resources. It provides resources to the projects and maintains track of how they are used. In addition, RA is responsible for sharing resource free-up information with the PAs. The procedure carried out by RA is as follows:

Step 2.1 Receives requests from all PAs of active projects M_{act} current period τ.
Step 2.2 Receives average resource requirements Avg_R_{gi} from all active PAs
Step 2.3 Calculates resource availability and resource suitability upon received requests for all active projects
Step 2.4 Calculates the M_{act} PAs' resource free up information (RFI)
Step 2.5 Allocate resources to all active projects and inform all PAs
Step 2.6 Receive "Update time" message from MA

Main Agent (MA): The main agent is a coordinating agent in charge of identifying conflicts emerging from project resource requirements and allocating those resources to the projects. It Coordinates the dynamic model with the project agent and resource agent.

Step 3.1 Initialize PAs and RA for starting if PAs register any active project to project dynamic model in current period τ
Step 3.2 Receives project information from all PAs, project dynamic model, and resource information from RA
Step 3.3 Inform project activity information to RA to update RAI and also message PAs who did not receive resources due to unavailability
Step 3.4 Iterate until 'Project done' is received from PAs
Step 3.5 Inform RA and PAs to 'Update Time' for the next time window
Step 3.6 'STOP' if all projects are completed. Else, trigger 'Initialized project activity' to PAs and RA

4. Scenario analysis

We considered 5 projects with the same number of tasks for the initial scenario analysis. As for the resources, we considered 4 different sets of resources with different skills to define multi-skilled resources. Table 1 shows the project tasks list, and Table 2 represents the resource types. Figure 3 shows the network diagram of the projects. In a multi-project environment, resources are scarce and used through a shared resource pool, and they obtain different skills from one another. Hence allocation of a suitable resource to a project based on its requirements is often complex due to unavailability.

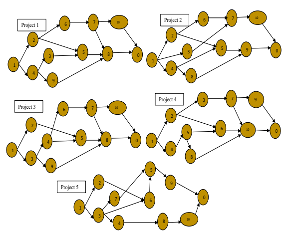

Figure 3. Network diagram of the projects.

For management convenience, each project is managed by a project agent who takes charge of the project scheduling and resource allocation within the project. However, the resources are still controlled by the resource agent of the resource pool. The problem the resource agent faces is how to allocate these resources over the five projects to gain maximal utilization of the resources, which will increase the performance.

Table 1. Projects with the task list.

Project Name	Project Tasks
Project 1	32
Project 2	32
Project 3	32
Project 4	32
Project 5	32

Table 2. 4 different sets of resources.

Resource type	No. of resources
Resource set 1 (R1)	25
Resource set 2 (R2)	25
Resource set 3 (R3)	25
Resource set 4 (R4)	25

4.1. Assumptions for scenario analysis

For the scenario analysis, the following assumptions have been considered

i. A human resource can contribute to different projects in each period t Ɛ T

ii. In the combination solutions of human allocation in every activity, personnel cooperation starts meanwhile and finishes simultaneously, and personnel can evacuate until the task is completed.

iii. All resources are assigned to the projects at the beginning

iv. It is assumed that no new resources will be hired during the development period

v. 0～1 decision variables

a. To record the allocation of workload

b. To count the assignments of WFs to projects

4.2. Computational results

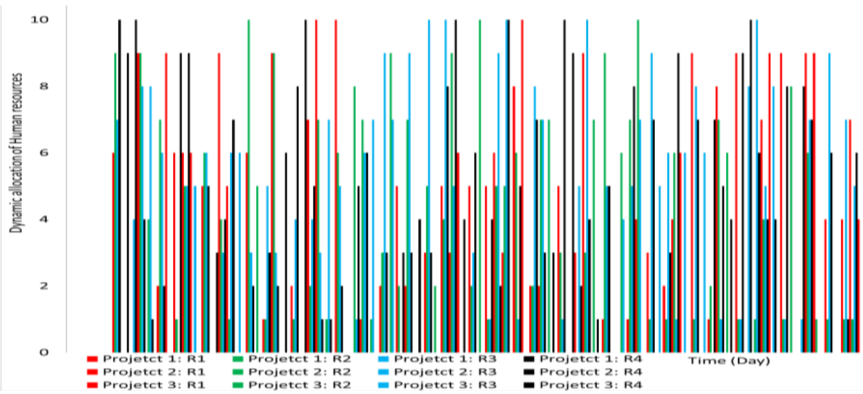

Figure 4. Allocation plan of resources based on project types (resource utilization).

Based on the project and resources information and assumptions, we did the simulation run to obtain the optimal resource allocation solution for the projects. The obtained assignments of these resources to the projects are shown in Figure 4 and Table 3. Figure 4 shows the resource utilization according to projects at each time. As mentioned before, 4 types of resources are used to develop 5 projects. Hence the resources are allocated to the projects based on resource availability and the necessity of resource types. From this Figure, the following are obtained. (1) The resource are assigned to projects dynamically since the demanded quantity changes over time. (2) Because the given amount is the same in some continuous intervals, it is not essential to allocate resources during the projects for each period. (3) This also reflects that the allocation period length influences the allocation results. This analysis also found that activities that need the same resources have been staggered because the total resource quantity is insufficient to implement these activities simultaneously. This indicates that the resource allocation impacts the scheduling over the projects, although the company manager does not control the project scheduling directly. Hence, the resource allocation on the upper level can affect the decision on the lower level. These detailed results can assist the decision-makers on both the upper and lower levels in making the appropriate resource allocation plans. Table 3 represents the optimal allocation of the resources to each project. In this allocation, we can see that the value is zero in some periods, representing resource insufficiency and unsuitability. Through this analysis, a decision-maker can get insights into how different types of resources would be allocated to the projects based on necessities.

Table 3. Allocation plan of resources based on project types (resource utilization-data table).

Time	R1					R2					R3					R4			
	P1	P2	P3	P4	P5	P1	P2	P3	P4	P5	P1	P2	P3	P4	P5	P1	P2	P3	P4
1-5	4	1	5	8	1	7	1	1	6	1	5	5	3	0	5	5	4	6	5
6-10	6	2	3	3	2	4	4	3	7	3	6	1	4	7	3	4	0	5	5
11-15	5	0	1	6	4	3	2	0	5	6	5	4	5	4	4	7	4	4	6
16-20	4	1	1	7	4	5	2	3	4	4	6	2	2	6	3	6	1	4	6
21-25	5	2	7	3	2	4	1	3	5	1	5	2	5	5	3	5	1	3	6
26-30	3	0	5	7	3	7	3	4	6	4	3	1	7	6	3	5	3	0	4

In practice, to improve resource usage, the assigned resource is transferred to each project at the beginning of each period.

In the end, idle resources should be released back into the resource pool if they are not required for a project in the following period. This resource transfer records the transferred resource quantity between the company resource pool and the projects. The average convergence curves of each activity schedule for all projects are shown in Figure 5.

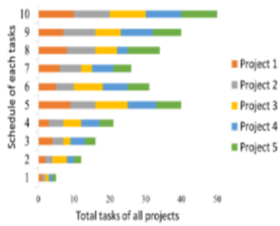

Figure 5. The Schedules of all projects (resource utilization).

5. Discussion

The model proposed in the paper can be the basis for designing decision support systems in the allocation and configuration of resources in MPM. Considering many features of resources in the model significantly increases the possibility of their structure and the flexibility of assignment to tasks. On the other hand, the proposed model assumes the invariability of project schedules, which significantly simplifies its computational complexity and eliminates the need to solve the problem additionally. In the paradigm, there are two levels of decision-makers. One decision-maker is the RA, who hopes to allocate resources to multiple projects based on project requirements, resource availability, and suitability. Another is the PA, where each PA of the respective project attempts to schedule their project to minimize project duration under resource constraints. In addition, the uncertainty associated with activity duration has been explicitly considered in the model. Finally, the project dynamic model to obtain cause and effect is developed using system dynamics. On the other hand, an agent-based system monitors and controls resource and project specifications through RA and PA. Furthermore, the communication between the project dynamic model and RA and PA is done through the main agent monitors the overall process. Finally, the efficiency of the proposed model was evaluated using a scenario example. In contrast to prior studies, the proposed model shows that it was able to deal with a multi-project resource allocation. From the computational analysis demonstrated in section 4.2, it has been obtained that when we have limited multi-skilled resources and demanded quantity of resources for each project changes overtime, the resources are assigned to projects dynamically. Also, because the given amount is the same in some continuous intervals, it is not essential to allocate resources in each period. The analysis also shows that the value is zero in several periods in this allocation, indicating resource scarcity and unsuitability. These outcomes reflect the research questions defined at the beginning. The shared resource pool used in the system allocates human resources across individual projects with required skill requirements and makes optimum use through scheduling. Moreover, compared to the literature, the fully developed system will have the ability to deal with possible on-the-fly changes resulting from various sources of uncertainty. This method will incorporate optimization techniques with agents' behavior logic to increase their intelligence, resulting in optimal decision-making for both short and long-term goals. In any field of work, human resources are critical. However, when working on multiple projects, each one has a specific aim requiring a diverse set of skills. The decision-makers in this model collaborate as a multi-skilled team, which is an integral part of transdisciplinary engineering research. The decision-support system can be considered a transdisciplinary-enabling framework to support the systemic integration of knowledge, with decision-makers acting as stakeholders. As a result, this study will significantly impact transdisciplinary engineering.

6. Conclusion

This paper has considered a multi-project resource allocation problem with multi-skilled resources. Each project comprises a series of tasks with different priorities that require different amounts of local and pooled resources. The aim is to complete all the project activities, satisfy precedence and resource constraints, and minimize each project schedule length. We developed an integrated simulation system to facilitate multi-project resource allocation and decision-making under uncertainty. Furthermore, the simulation results can be used to build a reusable knowledge base, and this information can be reused in other projects. However, this concept of integration is still in the early stage of development. It requires extensive further investigations to sort out the best solutions to produce a well-rounded multi-project simulation model. Nevertheless, the main contribution of this paper is to show how to integrate and use these models to study the multi-project environment. The following steps in the research are to define more complex relationships and parameters, ultimately creating a complete working simulation model. Then, we will make more precise modeling according to different actual situations, such as constraint and objective function, to be applied more accurately and flexibly.

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References

[1] T. Abdel-Hamid, and S.E. Madnick, *Software Project Dynamics: An Integrated Approach*. Englewood Cliffs, NJ, Prentice Hall, 1995.

[2] B. Lee, and J. Miller, Multi-project management in software engineering using simulation modelling, *Software Quality Journal*, 2004, Vol.12(1), pp. 59–82.

[3] Z. Laslo and A.I. Goldberg, Resource allocation under uncertainty in a multi-project matrix environment: is organizational conflict inevitable?, *International Journal of Project Management*, 2008, Vol. 26, pp. 773–788.

[4] C. Po-Han and M.S. Seyed, Hybrid of genetic algorithm and simulated annealing for multiple project scheduling with multiple resource constraints, *Automation in Construction*, 2018, Vol. 18, pp. 434–443.

[5] S.M.T. Fatemi Ghomi and B. Ashjari, A simulation model for multi-project resource allocation, *International Journal of Project Management*, 2002, Vol. 20, pp. 127-130.

[6] F. Haghighi Rad, and S.M. Rowzan, Designing a hybrid system dynamic model for analyzing the impact of strategic alignment on project portfolio selection, *Simulation Modelling Practice and Theory*, 2018, Vol. 89, pp. 175–194.

[7] J. Zulkepli, T. Eldabi, and N. Mustafee, Hybrid simulation for modelling large systems: An example of integrated care model, *Proceedings IEEE Winter Simulation Conference*, 2012, DOI: 10.1109/WSC.2012.6465314.

[8] M.T. Khatun, K. Hiekata, Y. Takahashi and I. Okada, Design and management of software development projects under rework uncertainty: a study using system dynamics, *Journal of Decision Systems*, 2022, pp. 1-24.

[9] W. Wakeland, L. Macovsky and G. An, A hybrid simulation model for studying acute inflammatory response, *Proceedings of the 2007 spring simulation multi-conference*, Norfolk,Virginia, Volume 2 Society for Computer Simulation International, 2007, pp. 39-46.

[10] A. Alvanchi, S. Lee and S. Abourizk, Modeling framework and architecture of hybrid system dynamics and discrete event simulation for construction, *Comput. Aided Civil Inf. Eng*, 2011, Vol. 26, pp. 77–91.

[11] J. Pajares and A. López, New Methodological Approaches to Project Portfolio Management: The Role of Interactions within Projects and Portfolios, *Procedia - Social and Behavioral Sciences*, 2014, Vol. 119, pp. 645–652.

[12] D. Hoffmann, F. Ahlemann and S. Reining, Reconciling alignment, efficiency, and agility in IT project portfolio management: Recommendations based on a revelatory case study, International *Journal of Project Management*, 2020, Vol. 38(2), pp. 124–136.

[13] P.K. Dey, Integrated project evaluation and selection using multiple-attribute decision-making technique, *Int. J. Production Economics*, 2006, Vol. 103 (1), pp. 90–103.

[14] K. Yaghootkar, and N. Gil, The effects of schedule-driven project management in multi-project environments. *International Journal of Project Management*, 2012, Vol. 30(1), pp. 127–140.

[15] F. Li, Z. Xu and H. Li, A multi-agent based cooperative approach to decentralized multi-project scheduling and resource allocation, *Computers and Industrial Engineering*, Vol. 151, 2021, 106961.

[16] M. Kannimuthu, P. Ekambaram, B. Raphael and A. Kuppuswamy, Resource Unconstrained and Constrained Project Scheduling Problems and Practices in a Multiproject Environment, *Advances in Civil Engineering*, 2018, 9579273.

[17] M.T. Khatun, K. Hiekata, Y. Takahashi and I. Okada, Dynamic Modeling of Resource Allocation for Project Management in Multi-Project Environment, *Advances in Transdisciplinary Engineering*, 2021 Vol. 16, pp. 223-232.

[18] G. Ilati, A. Sheikholeslami and E. Hassannayebi, A simulation-based optimization approach for integrated port resource allocation problem, *Promet Traffic Transport*, 2014, Vol. 26, pp. 243–255.

[19] N.P. Archer and F. Ghasemzadeh, An integrated framework for project portfolio selection, *Int. J. Project Management*, 1999, Vol. 17 (4), pp. 207–216.