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Research Article

# An Uncertain Resource-Constrained Project Scheduling Approach for Flexible Action in Reaction to Perceived Environment Conditions

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**Abstract**

In construction projects, there is a likely possibility of changing the activities duration due to operational errors or any change in the schedule of the signed contracts. Therefore, providing a flexible approach with the ability to quickly updating the project schedule is of particular importance to planners. In this article, we have tried to consider the sources which affect the project schedule such as activities, resources, and contracts as an autonomous and adjustable agent so that after a change in any of them, easily and with the least time to get a new updated schedule. To realistically achieve this specific goal, by precisely defining a control agent, a combination of agent-based simulation modelling and discrete-event simulation in the sophisticated AnyLogic7 software is tentatively proposed. The main contribution and distinction of this paper compared to the same researches is that the contract agent is considered as an independent factor for multi-factor project scheduling system. This factor is in interacts with the other factors such as resources and methods of doing activities; so, the administrator could make the necessary changes to this factor, in order to achieve an updated schedule for the start and end of each activity and the final time of the project. It is worth mentioning this method has a very high simplicity and flexibility compared to existing mathematical modelling methods and has the necessary potential to cover a variety of random events.

**Keywords:** Resource-Constrained Project Scheduling Problem, Agent-Based Simulation, Discrete-Event Simulation, Contract Agent, Flexibility.

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## 1. Introduction

In construction projects, the possibility of changes after the start of the project is inevitable, so it is important to pay attention to scheduling flexibility in the event of changes. Traditional scheduling and control systems based on hierarchical and centralized patterns are inflexible enough to adapt to the dynamism and complexity required by today's project environments. For this reason, successive suggestions for improving scheduling and control in a project management environment are constantly emerging. The success of a project is evaluated based on its performance in terms of time, cost, and quality. The resources constitute a critical factor that can have cause important effects on the time, cost, and even quality of the project. Delayed procurement of a resource may tend the activity to start with a delay. If the delayed activity is located on the critical path of the project activity network, the duration of the project increases, or the task may be performed with lower quality for overcoming the delay that has occurred. On the other hand, an increase in project duration may cause a delay in the deliverables of the project and, finally, an increase in the costs. Based on the conducted research, one of the major reasons for the occurrence of delays in project duration is poor management of the project contracts as well as changes made by the major contractors other than in procurement of the project resources [1]. Uncertainty in factors such as project contracts, activity duration, costs, technical complexities at executing time, and access to constrained resources causes changes to occur in project scheduling, for which the project managers should be capable to provide proper responses [2].

Project scheduling is performed for the creation of a timetable for all the project activities [3]. This is done with either a deterministic or a non-deterministic method. One of the most popular deterministic methods of scheduling is the critical path method (CPM), where the occurrence and runtime of each of the activities are assumed to be deterministic. PERT (Program Evaluation and Review Technique) is another scheduling method, where the activities have non-deterministic times, and three-point beta distribution is used for estimation of the time of each activity [4-7]. In PERT method, all relationships between activities are of FS type with zero lag while in the new research, this constraint is not considered; This method is called PLET (Probabilistic Linkage Evaluation Technique) where all types of relationships between activities is possible [8]. In PERT method, duration time of activities is stochastic whilst in some projects, occurrence of an activity may also be stochastic; to scheduling the projects of this type, GERT procedure and simulation techniques are proposed [9, 10].

By considering the constraints on the resources, project scheduling methods developed further as RCPSPs (Resource-constrained project scheduling problems). Studies show that as few as 48% of construction project managers consider resource constraints in project scheduling [11]. The RCPSP is defined in many studies as an NP-hard problem with different objective functions such as project time minimization (makespan) and total cost minimization with constraints on observation of the precedence relationships and the levels of access to the resources [12]. Samer Ben Issa, Yiliu Tu by classifying how to carry out activities, have studied and analyzed the types of these issues [13].

According to peer-reviewed research, flexibility in the face of change is an issue that needs to be addressed in today's project control issues. One of the most important changes that can make the project schedule difficult for its executive staff is the change in contracts related to the use of resources in the project. Failure to pay attention to this point, which has not been explored in previous research, can lead to a flexible schedule for changing. On the other hand, the existing complex mathematical methods with objective functions and their heavy limitations in solving project scheduling problems make it more difficult to pay attention to flexibility in solving such problems. Therefore, it seems necessary to pay attention to providing innovative solutions based on simplicity and flexibility when changes occur.

What distinguishes the present study from other research is the effect of contract changes on project scheduling. To this end, we have defined a project schedule as a multi-agent system and defined the contracts of a project as an independent factor, in which by changing the schedule of these factors, anyone can be monitored the modification at the start and finish time of each activity and the completion time of the project. In such a way that a flexible schedule can be provided so that the schedule can be updated by changing the contract of each resource or the lead-time of their procurement. Therefore, in this research and in section 2, we have discussed in detail the RCPSP and a variety of simulation methods. In section 3, the proposed simulation method of this research is presented. In Section 4 and 5, a number of examples are given, and then by proposed approach is modeled, and solved and the answers obtained are compared with other researches and the results obtained from standard problems. Finally, in Section 6, the effect of contract changes on scheduling is considered by presenting a scenario, and the results are obtained and analyzed with the proposed approach.

## 2. The State of the Art

In this section, we review the basic concepts of Resource-Constrained Project Scheduling Problem (RCPSP) and the simulation method approaches.

### 2.1. Resource-Constrained Project Scheduling Problem (RCPSP)

There are several methods for classifying project scheduling issues. One of the most popular of these methods involves their classification into three fields: α | β | γ. α is the resource specifications, β is the activity profile, and γ is the optimization criterion. We seek in this paper to model and solve what is traditionally shown as MPS | Temp | $C_{max}$. Here, MPS is a Project Scheduling, Temp stands for temporary constraints, meaning that there are different types of relationships between activities, and $C_{max}$ is the classical criterion for minimizing project time, i.e. makespan [14]. The RCPSP problem is classified into six classes [15]. In this classification, the common goal function is usually to minimize the project completion time, and their differences in problem modes include single-mode or multi-mode mode of how activities are performed. The six classification classes are: basic single-mode RCPSP, basic multi-mode RCPSP, RCPSP problems with non-regular objective functions, stochastic RCPSP, bin-packing-related RCPSP problems, and multi-resource constrained project scheduling problems (MRCPSP).

Many accurate methods have been presented based on the branch-and-bound framework for solving the RCPSP [16, 17]. There are also plenty of heuristic approaches for solving the RCPSP, which include methods based on prioritization rules [18], metaheuristic methods, such as the genetic algorithm [19], Tabu-search algorithm [20], simulated annealing (SA) approach [21], ants algorithm [22], particle swarm (PSO) algorithm [23], cuckoo search algorithm [24], hybrid metaheuristic algorithms [25-27] and simulation-based optimization, for instance, Generalized Stochastic Petri Net (GSPN)[28].

Modeling the RCPSP and solving it in construction projects involves thousands of individual activities, and it is very difficult and requires considerable time to be spent to find an accurate solution for this purpose. As an improvement over earlier research, Horenburg, Wimmer [29] have introduced the method of multi-agent systems (MAS), where the agent-based technique has been employed for the activities and resources. The independent agents of the processes record their activities at a central board, where all the agents can interact and negotiate resource allocation. Multi-agent systems defined as a branch of “distributed artificial intelligence,”[30] and regard it as a new method for solving problems through interaction between autonomous agents to simulate complex systems [31]. A variety of metaheuristic and combined methods, for example MAS method have been compared for solving the RCPSP problem [32].

Although RCPSP can be patterned with $\alpha \mid \beta \mid \gamma$ categorized and highlighted, but a functional classification should take into account the limitations and environment of the project in its model. In particular, model-based constraints can be added to make the problem more customizable for practical examples. Problems can be modeled in a static environment where all tasks are available before scheduling begins, or problems can be considered in a dynamic environment that may be timed while other activities are underway to enter the planning process. Based on the literature, it can be stated that at least 5 main factors affect RCPSP issues: activities, resources, objective functions, constraints and project environment. In this research, project scheduling has finally been performed using the agent-based technique and discrete event simulation, and evaluated through multiple experiments. The idea of multi-agent systems is a new scheme for information system architecture that dates back to two decades ago, and is very versatile today in the areas of robotics, artificial intelligence, information distribution systems, etc.

## 2.2. The Simulation Method Approaches:

Based on literature review[33], there are three simulation modeling methods or schemes, as follows, which can basically help the system designer to make a plan or model of the real world:

- ✓ Dynamic systems consider the individual entities and objects in an abstract fashion, and are focused on summarization of the inventories and feedback flows and loops.
- ✓ Discrete event modeling is based on the process-oriented view and approach, where system movement is represented based on the sequence of different operations performed on the entities.
- ✓ Agent-based modeling is based on the system designer's description in terms of the individual entities or objects and the possibility of their interaction with each other and with the environment.

Different methods of modeling can be employed in different problems given the purposes of simulation, available information, and the nature of the model. Nadoli and Biegel [34] have proposed the application of multi-agent simulation in intelligent manufacturing. Sridhar, Sheikh-Bahaei [35] have presented a hybrid methodology of agent-based architecture, discrete event systems, and soft computing for simulation of robots and network security systems. Alvanchi, Lee [36] have utilized hybrid modeling in the manufacturing and assembling industries. They have used dynamic systems for modeling capital level behavior and discrete event systems for modeling construction operations. Khedri Liraviasl, ElMaraghy [37] have utilized hybrid modeling methods in assembly lines. They have used the agent-based approach for modeling the behavior of assembly robots and discrete systems for representing the process transportation system sequence, and have implemented the hybrid model in AnyLogic7. Mustafee, Powell [38] have addressed in detail the definitions, applications, and challenges of different hybrid modeling approaches. One of the applications of agent-based modeling is scheduling problems. Agnetis, Billaut [39] have dealt with its applications for solving scheduling problems in the different areas, such as the applications of these systems in multi-project scheduling problems, where limited renewable resources like manpower and equipment are available. Liu and Mohamed [40] have presented a structure for resources and their allocation to different activities using the agent-based modeling layout. Presentation of the notion of project scheduling using the agent-based technique and its combination with discrete-event simulation has been investigated in Horenburg, Wimmer [29]. The quality and duration of the computations have also been assessed through different methods there, and it has finally been proven that the method is consistent and reliable for scheduling construction projects.

The unique characteristics of multi-agent systems include distribution capability, frequency, creativity basis, and virtual learning, as a result of which they can be regarded as a replacement for earlier software systems in specific applications [41]. This range of modeling can be applied to many operations research problems, such as the traveling salesman problem [42], production scheduling problems [43], supply chain management [44], job shop production scheduling problems [45], aircraft maintenance manning [46], inventory policy behaviors

[47], disease transmission modelling [48] and also coordination of project scheduling changes [49].

Due to the growing complexity in project scheduling problems today, conventional methods of solving the RCPSP problem lack the necessary capability of presenting proper solutions. Multi-agent systems have maintained the strengths of conventional methods, and successfully improved the quality of problem solution by combining with learning methods as well as using the characteristics of agents (such as improvement in project performance indicators, schedule generation speed, generated schedule flexibility, etc.) [50]. According to Knotts, Dror [42], the RCPSP alone is an NP-hard problem; therefore it seems unlikely to find an accurate problem solution algorithm for solving the real-sized problems within a specific operating time. Furthermore, the activities definitely have non-deterministic durations in the real problems. It is therefore clear that heuristic methods are proper approaches to solving these problems.

A variety of mathematical stochastic methods are presented to consider various types of uncertainty situations in project scheduling issues. On the other hand, they provide appropriate models for considering these conditions of uncertainty plus other limitations in addressing these issues, such as constrained resources, and the existence of probabilistic times for activities adds to the complexity of the issues, and makes them very difficult to handle. However, the ability to simulate combinational methods, as in this article, which combines a multi-agent and a discrete event approach, results in a high degree of simplicity and flexibility, and does not require long, bulky models. Moreover, using simulation software capabilities, relevant solution can be obtained through appropriate repetitions at the right times. In other words, the underlying operating methods are of great simplicity at the time of making the model, as well as at the response time, besides their ability to add a variety of constraints and uncertainty situations by adding new agents. Table 1 summarizes the other reviewed papers on the application of simulation in project management.

**Table 1.** Summary of papers which are applied simulation in project management

| References | Method | | | Results |
|---|---|---|---|---|
| | System dynamics | Discrete event systems | Agent based | |
| [51] | ✓ | | | System dynamics models are not built under an organized framework. They provide a regular analysis of management issues, but are not including the operational translation |
| [52] | | ✓ | | Results for four different resource levels for project duration |
| [53] | | ✓ | | This model can be used to evaluate project plans and risk management. Further understanding of the behavior of engineering design processes has been done in this research |
| [54] | | | ✓ | An agent-based software for scheduling multiple projects that can be integrated into an existing ERP system |
| [55] | | ✓ | | This model can be used as a tool to test different cooperation policies. The project manager can use this model to convince a subcontractor to see the value of cooperative processes. |
| [56] | ✓ | | | The benefits of hiring programmers over adding overtime are discussed. In the end, overtime is sometimes better than hiring. |

**Table 1.** Summary of papers which are applied simulation in project management

| References | Method | | | Results |
|---|---|---|---|---|
| | System dynamics | Discrete event systems | Agent based | |
| [57] | ✓ | | | Negative impact on system-level learning when relationships are unstable and interdependent between firms. |
| [58] | | ✓ | | Provides the use of statistical tools for risk management as a cost-effective option. |
| [59] | ✓ | | | Estimating the Impact of Enterprise Resource Planning Project Management Decisions on Post-Implementation Maintenance Costs. The main findings of the simulation show that the initial investment in training and system exposure translates into long-term cost savings. |
| [60] | | ✓ | | The cost simulation approach has been a simple decision tool for fairly evaluating the costs of construction projects and presents uncertainties based on the judgment of experienced project managers. |
| [61] | | | ✓ | Applying Reinforced Learning Based on Multi-Agent Systems to Provide High Quality Solutions to the MMRCPSP Problem |
| [62] | | ✓ | | Provide extensive functionality for advancing Monte Carlo simulation for project management |
| [63] | | | ✓ | Using agent-based modeling to solve the MMRCPSP problem. Project activities are considered as factors Which will lead to the creation of a multifunctional system in the form of a node network or AON. Each factor has two tools for decision making: 1) Automatic learning and 2) Potential local distributor based on innovative method. |
| [64] | | | ✓ | Proposing a Agent-based simulation model to assess project risks, This model makes it possible to test different risk reduction strategies to measure their impact on the project |
| [65] | | ✓ | | Provide a simulation-based optimization method to solve the RCPSP problem in conditions of uncertainty in order to minimize project time |
| [66] | | | ✓ | Investigation of different strategies in project bidding management, based on the presentation of a multifactorial simulation model |
| [67] | | ✓ | | Monte Carlo simulation can help project managers estimate the potential risks assigned |
| [68] | | | ✓ | Proposing an agent-based simulation system to address the challenges of multi-project limited resource planning under uncertainty. |
| [69] | | | ✓ | Applying the multi-factor simulation method to solve the RCPSP problem in situations where the activities do not stop more than once. In this article, two factors of activity and timing that have the ability to interact and negotiate with each other have been used |

In the conceptual model of this research, a combination is presented of the agent-based modeling method and discrete event systems as well as the quality of interaction between the agents in the discrete space of the project. Following that model, we also seek in this paper to employ the flexibility of the presented model by combining the agent-based modeling method and discrete event systems to generate a space full of changes in project scheduling. We can thus identify any agents that can cause changes to occur in the project space, and access safer solutions by combining them in the project simulation environment.

## 3. The Proposed Method: Simulation approach on RCPSP Modeling

The model presented in this study follows to provide the main frameworks for project scheduling under agents that have the capability of making decisions based on the defined rules. These agents include activity, resource, and the contract agents. The model has been designed based on the mechanism of interaction between these agents. The major tool for interaction between agents involves sending messages at the desired times. Messages are sent and received via the ports of each of the agents, and the communication lines connect the output and input ports of the agents to each other. A connection between two ports represents message communication between the agents.

### 3.1 Presentation of the Proposed Model

The main modules of the conceptual model presented in this paper are discussed below:

***Activity Agents:*** In this model, each activity is modeled as an agent, and the precedence relationships are defined through the ports convenient at the input and output of each of the activities. Activity agent duration can also be introduced as a random variable.

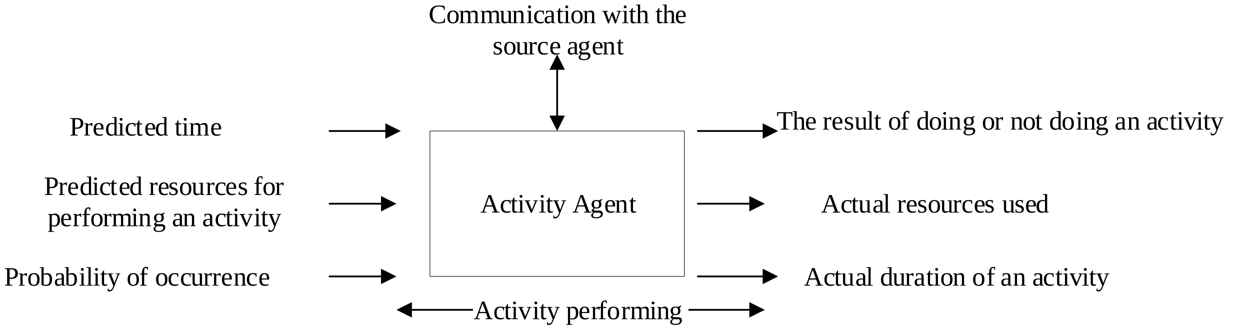



**Fig.1.** Activity Agent structure

As shown in Fig.1 the time and resources required to perform an activity and on the other hand the probability of their occurrence are predicted as the input of this agent. This agent is also related to the resource agent and its output is reported as doing or not doing it and the time and actual resources spent for this agent.

***Resource Agents:*** Each of the resources is also defined as an agent, which is managed by another agent, referred to as the *Resource Pool*. The resource pool is responsible for receiving requests from activities for allocation of the required resource as well as controlling the constraint level of the resource in question and allocating the resource to activities if possible. If the number of resources requested by various activities exceeds the defined available resource level, activities will wait until resources are released and allocated. An activity that requests a resource earlier has higher priority if there are no constraints, but the random prioritization method is used in case of unavailability of sufficient resources and also for allocation of resources to a few simultaneous qualified activities.

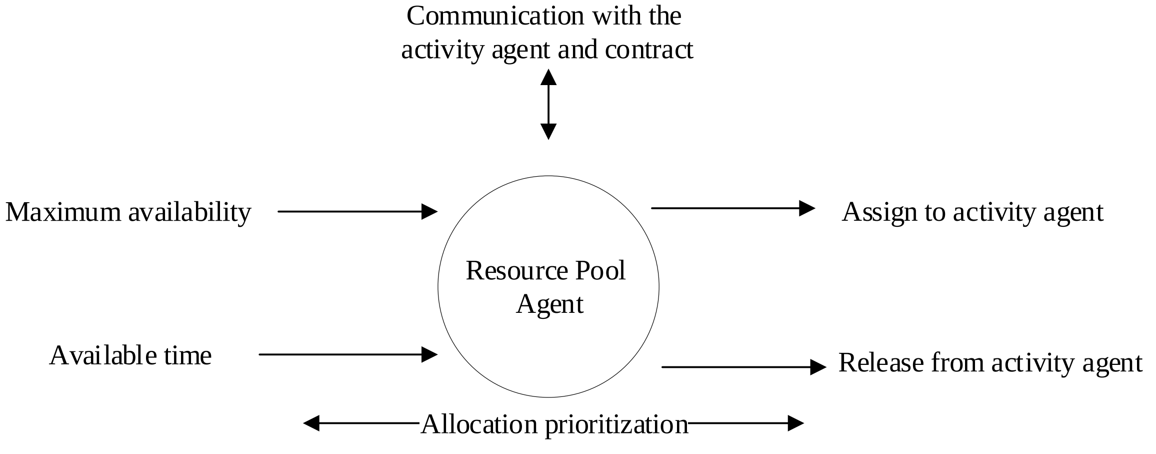



**Fig.2.** Resource Pool Agent Structure

As shown in Fig.2 the input and output of the Resource Pool Agent are shown. Accordingly, the input of a Resource agent includes the maximum number and time available and its output is allocated or released from activity. This agent prioritizes the activities based on the request and then assigns them to the activities

***Contract Agents***: What makes the present model different from those in similar research, however, is that it considers an agent referred to as the *Contract Agent*. This agent is capable of managing time for each of the resources based on the contracts made or constraints on the required supplies. For a more proper understanding, assume that an activity has been assigned to a contractor, and its beginning and end are scheduled using conventional methods of scheduling with the assumption that the resources are available at the required times (the constraint on the number of resources has been observed in each unit of time).

However, the contract may be postponed for whatever reason (for example, failure of the contractor to fund the contract), and the initial scheduling of the problem may be disordered, in other words, and the required resources that must be provided to the activity through the contract will become unavailable. Fig.3 shows the inputs and outputs of the contract agent. Accordingly, if the available time of each resource changes, the contract agent will update the schedule of all activities using the resource by applying time management. Fig.4 shows main conceptual model presented of this paper.

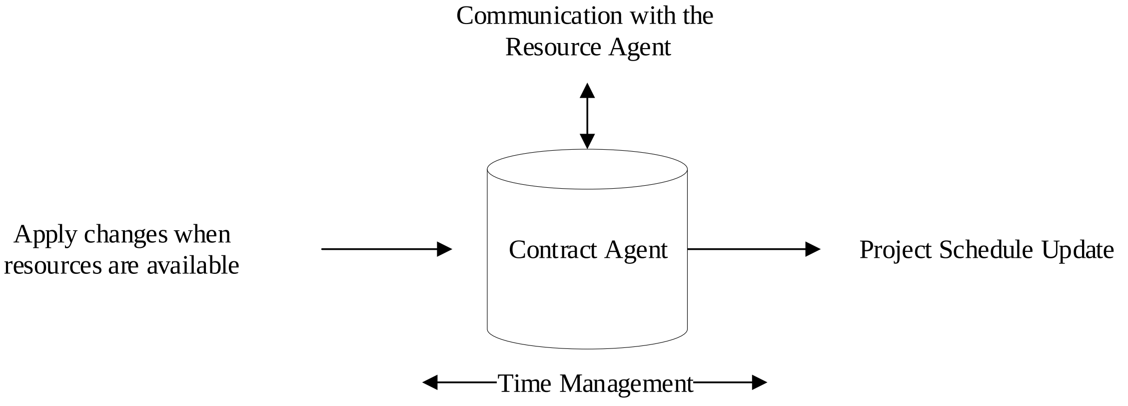



**Fig.3.** Contract Agent Structure

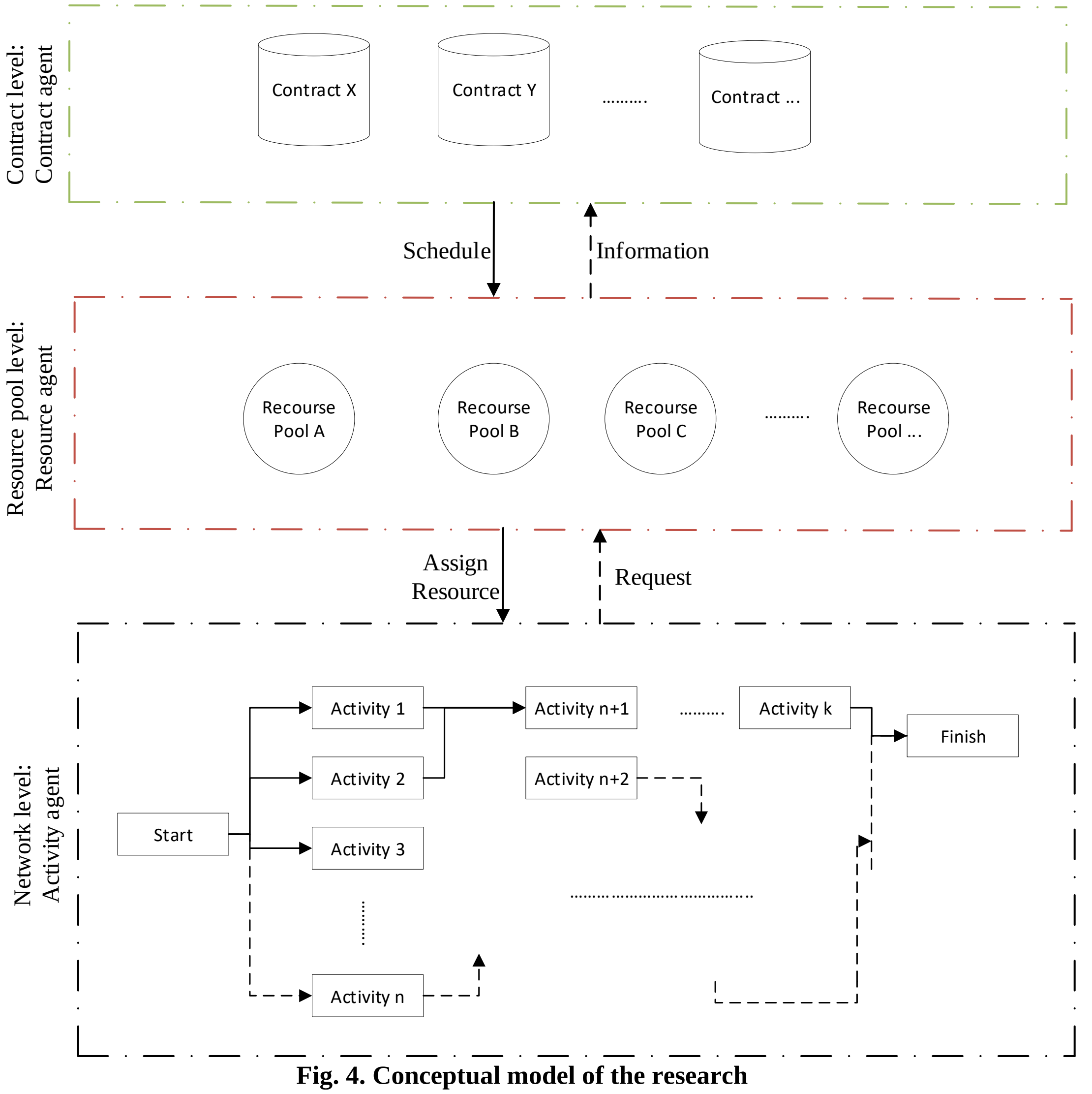



**Fig. 4. Conceptual model of the research**

As shown in Figure 4, the conceptual model of this research consists of three general levels. These three levels are:

**1- Network level**: In this level, the activity agent is defined. For each activity, the predicted time, required resources and the probability of its occurrence at this level are determined. It also determines how it takes precedence and latency over other activities at this stage. Activity transmits the amount, type of resource required, and duration of resource involvement to the second level (Resource Pool Agent) through the message communications specified in the form (Request).

**2-Resource Pool Level**: At this level, resource agents are defined. These factors are demanded based on the needs of the activities. Since a resource may be needed as many times at similar times, at this level activity prioritization patterns take place. Resources are allocated to activities based on the pattern of prioritization. This level, on the other hand, is related to the third level, the level of the contract. The information from each source is transferred to the third level.

**3- Contract level**: At this level, there are contract agents that are related to the second level agents. The main task of this level is to manage the time of each resource. Resources delegate their scheduling management to this level by submitting their information. In case of any change in the available resources, the contract agent manages the changes and updates the new schedule for the desired activities and the entire project schedule.

## 3.2 Translation of the simulation model to Anylogic7 ™

As also stated in the previous section, agent-based modeling enables us to get familiar with the behavior of a system by considering its components. AnyLogic7 is one of the simulation tools that make it possible for us to generate flexible models through the agents, which interact with each other and with their environments. Therefore, the modeling and implementation have been done using AnyLogic7 given its unique characteristics. For this purpose, the steps in Fig. 5 are implemented in AnyLogic7.

Based on the proposed process in Figure 5, the steps of the simulation model in Anylogic7 software are divided into 4 steps. In the first step, a simulation model is created based on which project activities and resources are defined. In the second step, resources are allocated to activities. In the third step, the conditions for performing the simulation and designing the necessary experiments are set, and finally, in the fourth step, the simulation model is implemented and the desired parameters are extracted. Each of these steps is described in detail below:

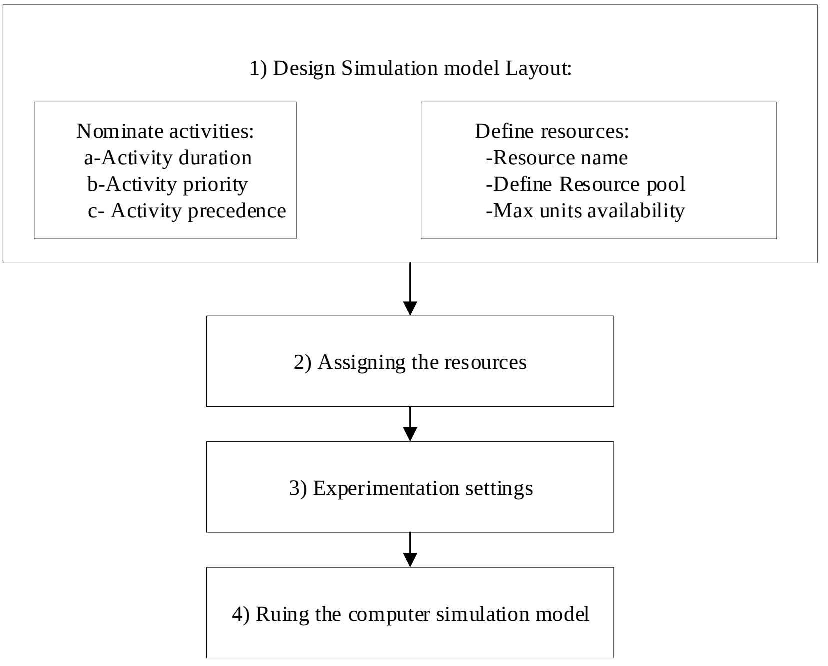



**Fig. 5**. Simulation modeling steps in AnyLogic7

### Step 1. Design simulation model layout

-*Nominate activities:* In the AnyLogic7 software, the Service agent is used for defining activities. In the "*Delay time*" row in the "Properties" section of the agent, the duration of each activity can be defined. In the "Task priority" section, a random number has been assigned as running priority to each of the activities using the *uniform_pos()* function (the function for generation of positive uniform random numbers) in cases where multiple activities can be run, and insufficient resources are available. In AnyLogic7, there are input and output terminals for each agent. Therefore, the precedence relationships are defined using these terminals and channels. The Source and Sink agents are also used as the start and finish nodes of the project network, respectively. Furthermore, the Split agent is used for activities with multiple outputs (multiple successor activities), and the Combine agent for activities with multiple inputs (multiple precedence activities). For calculation of the makespan of the project, the timeMeasureStart and timeMeasureEnd agents are used at the beginning and end of the project network.

*-Define resources*: For definition of a resource, the *Resource Pool* agent is used, and the resource name is registered in the "Properties" section. In the "Capacity" row in the "Properties" section of the *Resource Pool* agent, the maximum availability of each resource in each unit of time is defined.

### Step 2. Assigning the resources

In the "Resource sets" row in the "Properties" section of the *Service* agent, the number of resources of each type required for each activity can be determined. The *Service* agent automatically releases the allocated resources after the activity is performed.

### Step 3. Experimentation settings

The *Parameter-Variation* test in AnyLogic7 has been used for running the simulation model, where the settings and obtained results can be iterated *m* times. For this purpose, a new database table can be defined, where different columns such as project duration (makespan) and the beginning and end of each activity can be defined. The required coding commands, recorded in the "After simulation run" row in the "Java actions" section, help us to record mean project termination time after each run in the defined *makespan* column in the defined database (*output_data*).

**Step 4. Running the computer simulation model**

The *Parameter-Variation* test in AnyLogic7 has been used for running the simulation model, where the settings and obtained results can be iterated *m* times. The number of times simulation is run is recorded in the "Number of runs" row in the "Parameters" section.

## 4. Description of an example

Information on an example from Giran, Temur [70] is shown in Table 2. It is assumed in the example that there is one resource, and 7 units of the resource are available every day.

**Table 2**. Information on the Example [70]

| No. | Activity Name | Precedence | Duration (Days) | Required Resource |
|---|---|---|---|---|
| 1 | A | - | 6 | 5 |
| 2 | B | - | 3 | 3 |
| 3 | C | A | 4 | 2 |
| 4 | D | - | 6 | 5 |
| 5 | E | A,B | 7 | 3 |
| 6 | F | C | 5 | 4 |
| 7 | G | D | 2 | 4 |
| 8 | H | A,B | 2 | 5 |
| 9 | I | G,H | 2 | 3 |
| 10 | J | F | 6 | 1 |
| 11 | K | C,E | 1 | 3 |
| 12 | L | E,G,H | 2 | 3 |
| 13 | M | I,K | 4 | 2 |
| 14 | N | F,L | 2 | 1 |
| 15 | O | L | 3 | 5 |
| 16 | P | J,M,N | 5 | 3 |
| 17 | Q | O | 8 | 4 |
| 18 | R | D,O | 2 | 5 |
| 19 | S | P,R | 6 | 2 |
| 20 | T | Q | 2 | 1 |

The first thing to do when generating an agent-based model is to generate the agents. Agents are the initial generators of an agent-based model. Each agent is given a series of rules, based on which it should communicate and interact with the other agents. These interactions and communications form the overall behavior of the system. The above example has been modeled in AnyLogic7 given the approach of this research (Fig. 6).

In the model generated by the software, the *Service* agent has been used for modeling the activities, the *Resource Pool* agent for introducing the resources and the levels of constraint on their availability, the *Split* and *Combine* tools for observing the precedence of activities with multiple inputs or outputs, and the *timeMeasureStart* and *timeMeasureEnd* tools for calculating project duration. Furthermore, in the "Task priority" section, a random number has been assigned as running priority to each of the activities using the *uniform_pos()* function (the function for generation of positive uniform random numbers) in cases where multiple activities can be run, and insufficient resources are available.

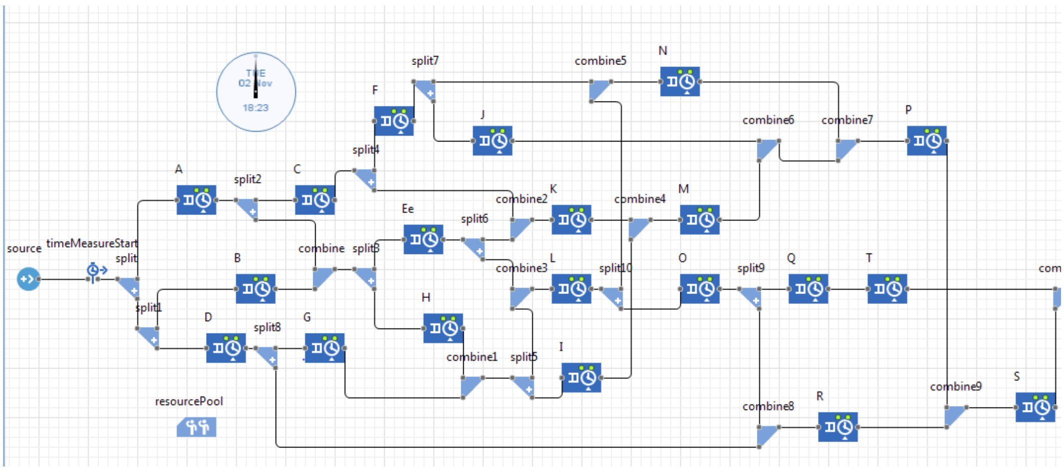



**Fig. 6**. Simulation model of the example with AnyLogic7

If the issue of *contract* agent is ignored, the problem will turn into a classic RCPSP, for solving which many methods have been proposed in different references. In the section on validation of the model, the obtained solution has been compared to theirs. The *Parameter Validation* test in AnyLogic7 has been used for running the simulation model, and the settings and results obtained in 5000 iterations. The final schedule diagram of the proposed model is shown in Fig. 7.

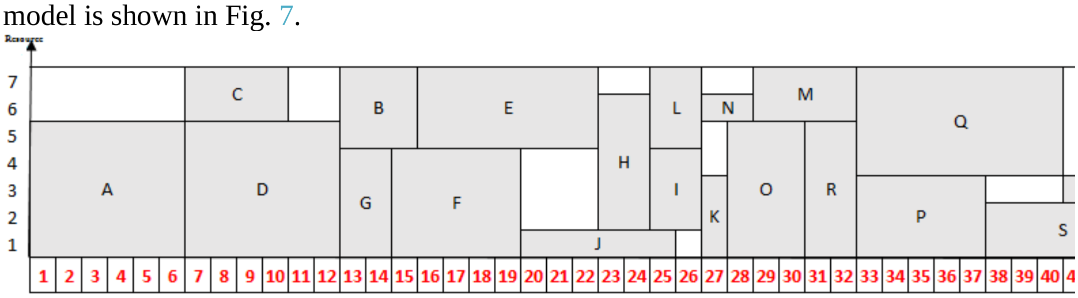



**Fig. 7**. Final schedule diagram of the activities

It should be mentioned that the beginnings and ends of the activities are different from the results in Giran, Temur [70]. In other words, the obtained solution is considered as another optimal solution to the problem. The total number of idle resources has been calculated in both methods as 48 resource-days.

## 5. Model validation

For ensuring the validity of the model presented in this paper, a large number of problems available in the reviewed papers were selected, and their results were compared to those of the proposed model. Extremely similar results were observed in all the cases.

To evaluate the efficiency of proposed solving procedure of this study, 15 standard examples from project scheduling database (sample electronic library, PSPLIB available at http://www.om-db.wi.tum.de/psplib/) have been selected. The PSPLIB is divided into four problem class: J30, J60, J90, and J120 in which 5 problems are randomly selected from these classes respectively. Comparison of results of proposed algorithms and the results of standard problems are given in tables 2-4. The results of the proposed method in solving standard problems are shown as 1000 and 5000 repetitions in Tables 3 to 5. Also, each experiment was repeated 30 times iterations and the results were compared with the optimal answers by using the non-parametric hypothesis of Wilcoxon Signed Rank Test. Since there is no evidence that the results obtained from solving various standard problems at different scales have normal distribution, the non-parametric Wilcoxon hypothesis test is used.

Based on this, the average value of makes pan obtained from the proposed method is repeated 1000 and 5000 times based on 30 interaction steps; 15 problems selected from the set of standard problems J30, J60 and J120 with its optimal value at 95% confidence level has been tested and solved. The p-value obtained in these tests is shown in Tables 3, 4 and 5.

**Table 3**. Results of purposed method and hypothesis test from optimal makespan set J30

| Randomly selected standard problem | Optimal makespan | Average makespan in 30 iterations | | Non-parametric hypothesis of Wilcoxon Signed Rank *(p-value)* | |
|---|---|---|---|---|---|
| | | Numbers of runs | | Numbers of runs | |
| | | 1000 | 5000 | 1000 | 5000 |
| J301_9 | 49 | 50 | 49 | 0.425 | 0.675 |
| J304_2 | 60 | 61 | 61 | 0.375 | 0.456 |
| J308_4 | 48 | 48 | 48 | 0.389 | 0.543 |
| J307_1 | 55 | 55 | 55 | 0.418 | 0.523 |
| J3013_9 | 65 | 65 | 65 | 0.479 | 0.480 |

The average makespan values are presented in Table 3 which are obtained from 1000 and 5000 iterations, respectively, as well as 30 rounds of simulation for solving 5 problems from the randomly selected J30 standard set. The obtained P-value values show that the mean obtained from the proposed method is not significantly different from the optimal answer and it can be concluded that the proposed method can be used to solve problems with dimensions of 30 activities.

**Table 4**. Results of purposed method and hypothesis test from optimal makespan set J60

| Randomly selected standard problem | Optimal makespan | Average makespan in 30 iterations | | Non-parametric hypothesis of Wilcoxon Signed Rank *(p-value)* | |
|---|---|---|---|---|---|
| | | Numbers of runs | | Numbers of runs | |
| | | 1000 | 5000 | 1000 | 5000 |
| J602_7 | 53 | 54 | 53 | 0.435 | 0.425 |
| J605_4 | 72 | 72 | 72 | 0.523 | 0.357 |
| J608_1 | 64 | 65 | 64 | 0.501 | 0.643 |
| J603_2 | 69 | 69 | 69 | 0.328 | 0.403 |
| J6014_3 | 61 | 62 | 61 | 0.339 | 0.520 |

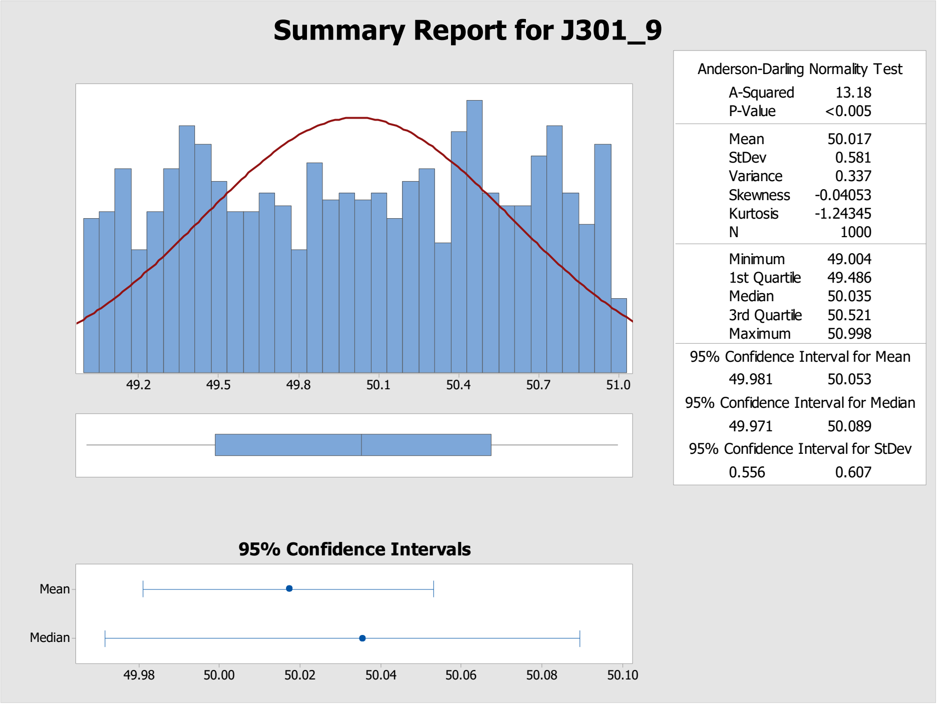
Table 4 shows the average makespan values obtained from 1000 and 5000 repetitions, respectively, as well as 30 times simulation for solving 5 instance problems from J60 standard set which are randomly selected. The calculated P-value values show that the mean obtained from the proposed method is not significantly different from the optimal answer and it can be concluded that the proposed method can be used to solve problems with dimensions of 60 activities.

**Table 5**. Results of purposed method and hypothesis test from optimal makespan set J120

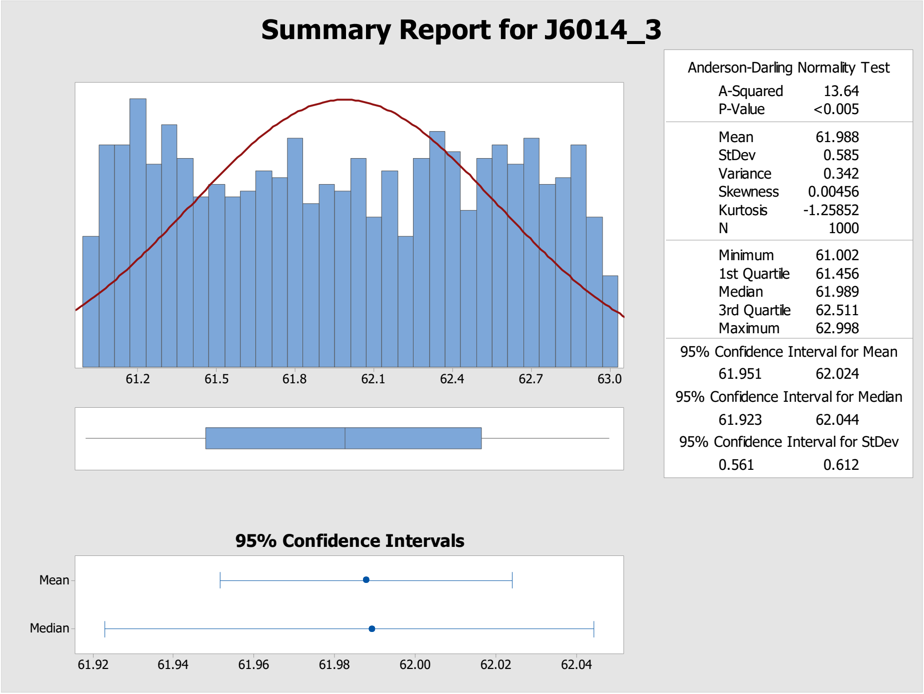
| Randomly selected standard problem | Optimal makespan | Average makespan in 30 iterations | | Non-parametric hypothesis of Wilcoxon Signed Rank *(p-value)* | |
|---|---|---|---|---|---|
| | | Numbers of runs | | Numbers of runs | |
| | | 1000 | 5000 | 1000 | 5000 |
| J1201_7 | 117 | 119 | 118 | 0.335 | 0.435 |
| J1203_8 | 77 | 77 | 77 | 0.346 | 0.423 |
| J1206_2 | 125-135 | 131 | 132 | 0.454 | 0.532 |
| J1207_2 | 113-114 | 115 | 113 | 0.235 | 0.326 |
| J1206_3 | 135 | 136 | 135 | 0.357 | 0.490 |

Table 5 shows the mean makespan values obtained from 1000 and 5000 repetitions, respectively, as well as 30 interactions for solving 5 problems that are selected randomly from J120 standard set. The interpretation of obtained P-value show that the mean obtained from the proposed method is not significantly different from the optimal response and it can be concluded that the proposed method can be applied to solve problems with dimensions of 120 activities and above.

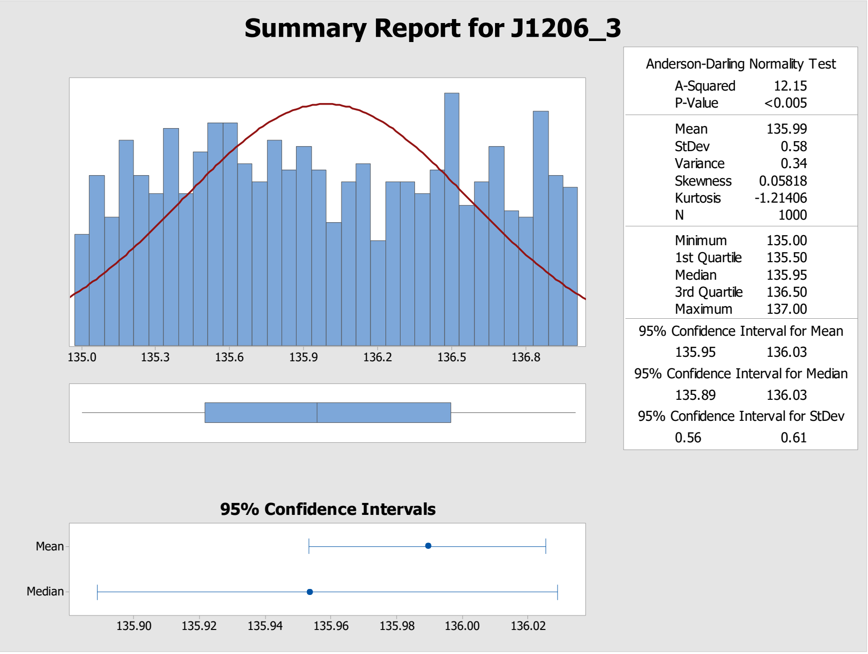
These results have been obtained on a computer with specifications including a Core i5-520M processor with Turbo Boost up to 2.93 GHZ.  Also, the makespan results obtained from the proposed method in comparison with the solution of the standard problem show that the median of this new method is not significantly different from optimal methods. Therefore, it can be said that the proposed method is effective for solving similar problems.


Summary Report for J301_9
Anderson-Darling Normality Test
A-Squared 13.18
P-Value <0.005
Mean 50.017
StDev 0.581
Variance 0.337
Skewness -0.04053
Kurtosis -1.24345
N 1000
Minimum 49.004
1st Quartile 49.486
Median 50.035
3rd Quartile 50.521
Maximum 50.998
95% Confidence Interval for Mean
49.981 50.053
95% Confidence Interval for Median
49.971 50.089
95% Confidence Interval for StDev
0.556 0.607
49.2 49.5 49.8 50.1 50.4 50.7 51.0
95% Confidence Intervals
Mean
Median
49.98 50.00 50.02 50.04 50.06 50.08 50.10

(a)


Summary Report for J6014_3
Anderson-Darling Normality Test
A-Squared 13.64
P-Value <0.005
Mean 61.988
StDev 0.585
Variance 0.342
Skewness 0.00456
Kurtosis -1.25852
N 1000
Minimum 61.002
1st Quartile 61.456
Median 61.989
3rd Quartile 62.511
Maximum 62.998
95% Confidence Interval for Mean
61.951 62.024
95% Confidence Interval for Median
61.923 62.044
95% Confidence Interval for StDev
0.561 0.612
61.2 61.5 61.8 62.1 62.4 62.7 63.0
95% Confidence Intervals
Mean
Median
61.92 61.94 61.96 61.98 62.00 62.02 62.04

(b)




(c)

**Figure 8.** Summary of statistical results of problem solving J301_9 (a), J6014_3 (b) and J1206_3 (c) using the proposed method

Figure 8 (8.a, 8.b and 8.c) summarizes the statistical results for solving instances J6014_3, J1206_3 and J301_9 respectively that presented the, mean, standard deviation, max and min. The maximum in solving these problems represents the worst case and the minimum represents the best obtained solution. 95% confidence intervals for mean, median and standard deviation are also provided.

## 6. Scenario design: Contract agent effecting

We would now like to consider conditions where the contract agent is also activated. For this purpose, we have made use of the Schedule agent in AnyLogic7. This agent will be capable of controlling and adjusting the resources defined in the simulation model. Figure 9 shows The Agent based Project scheduling Pseudo code.

```
Initialize phase
WBS ← project activity Agents;
; Res_Pool ← Project Resources Agent
; Cont_Pool ← Project Contract Agent
Project Scheduling Phase
Start
Do
Check all contracts from Cont_Pool ;
10 Contract Reviewing step
Apply contracts rule;
Select necessary resource from Res_Pool ;
Assign resources to activities;
schedule or re-Schedule the project;
```

```
End
if new contract receives Then
goto 10
else
if current contracts have been changed Then
goto 10
end if
while all contracts are applied to project
Finish
```

**Fig. 9.** Agent based Project scheduling Pseudo code

Let us assume that it is set through a contract when a resource is made available, and that the resource has become unavailable based on the changes made and failure to fund the contract since the beginning of the seventeenth day, and it is predicted that these conditions will continue until the end of the twenty-third day of the project. It is displayed in Fig. 10 how the *Schedule* agent is set for the available resource. The necessary changes are made in the contract at the appropriate time in the Start and Finish rows, and the availability of the resource in question is considered to be zero within this period.

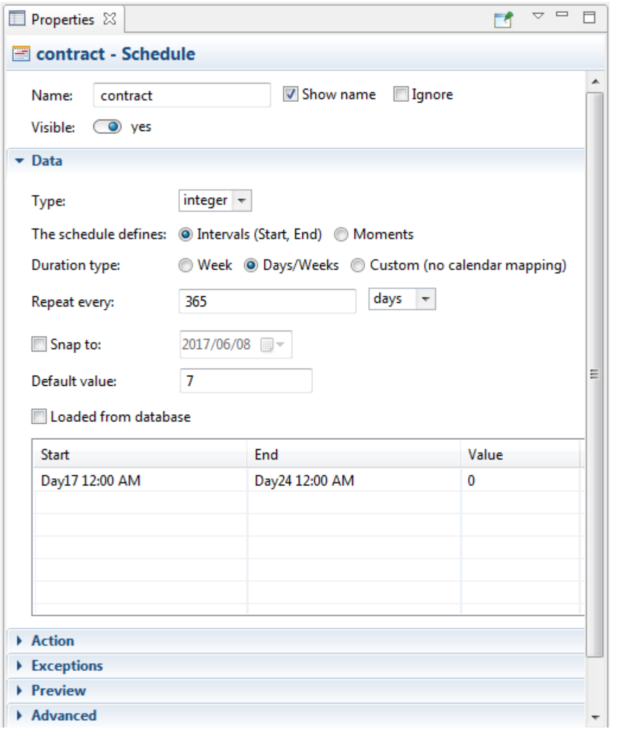



**Fig. 10**. Schedule settings of the Contract Agent

The necessary corrections regarding the dates concerned are made through the communication of information with the resource pool. For this purpose, the Resource Pool agent is activated in "Properties" and the "By schedule" option in the "Capacity defined" row, and the name of the scheduling agent, which is "contract" here, is selected in the "Capacity schedule" row. These settings cause the resource to become unavailable for 7 days from the beginning of the seventeenth to the beginning of the twenty-fourth day of the project.

It has been assumed that pauses are made possible in the activities in these conditions. If changes are made to the contract agent, as a result of which the resource becomes unavailable, this assumption helps regard part of the activity that has already been performed as acceptable, so that repetition is avoided. For this purpose, the “Task may preempt” option should be checked in the “preemption” row in the “Properties” section of the activity, and the “Wait for original resource” option, should be selected in the “Task preemption policy” row, according to the instruction reference for AnyLogic7 [71].

7-day delay occurring in the contract causes the project to be postponed for 11 days in average. It should be mentioned that the best solution observed during the test period has been calculated as 54 days for the project period. The schedule of each of the activities is shown in Fig. 11.

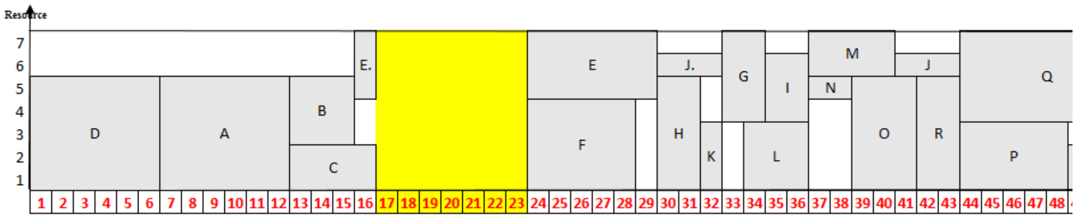



**Fig. 11**. Schedule Diagram of the activities with a delay assumed in the Contract

The yellow part in Fig. 6 represents the period during which the resource has not been made available to the project. Activities E and J have been postponed based on the schedule, where E has been active for 1 day, and the rest of its activity has been performed after the above period. Based on the change that has been made, the total number of idle resources has been calculated as 73 resource-days, which exhibits an increase of 25 resource days with respect to the previous case. In other words, not only should the 11-day delay in the project be considered for calculation of the cost of the changes that have been made, but the cost of the above number of idle resources should also be added to it.

## 7. Conclusion

So far, researchers have proposed various methods for planning and scheduling projects concerning limited resources. Since most of the proposed methods are based on mathematical optimization, following them is associated with challenges such as computational complexity and simplification. Achieving optimal solution in some cases requires more time and expenses to implement the optimization model, and to deal with it, metaheuristic methods that provide near-optimal answers are often followed. Dealing with the uncertainty in the time of activities, access to resources, number of available resources, conditions to release the resources, as well as prioritizing the assign resources in different time periods are other challenges in the project scheduling literature. Applying discrete-event simulation methods in the literature to be considered by some authors. Applying discrete-event simulation methods has been considered as an effective solution due to the modeling of main random effects and interactions as well what if analysis. Since stochastic events are an integral part of the project scheduling domain, we seek rapid, effective modeling techniques so that we can make changes, such as changes in project contracts, in the project scheduling problem. But what makes the present study different from its previous research is:

- The uncertain resource constraint project scheduling problem is considered.
- A combination of agent-based modeling and discrete event simulation is developed to solve uncertain RCPSP.

- The *contract agent*, which can change the project schedule, is proposed.
- The effect of delay in *contract agent* ratification and implementation on the presented schedule is analyzed.

Our proposed method in this paper, which combines multiple agents and discrete-event simulation, is presented using the capabilities of the Anylogic7 software, which has considerable simplicity and flexibility compared to mathematical modeling, and the results are also validated. This approach consists of scheduling construction projects using the method of resource allocation based on multi-agent systems. Therefore, the activities, resources, and contracts have all been modeled via independent agents to pursue their own objectives. Furthermore, an independent agent known as the contract agent can make the desired changes to the schedule in case of any changes in the quality of the contracts or resource supplies. Applying agent-based simulation approach led to the following results:

- Flexible and more rapid response in reaction to perceived environment conditions
- Solving project scheduling models in the form of a mathematical problem takes a lot of time and sometimes many changes are needed to implement them in the real world, but the simulation and its components allow us to spend the least time on the effect of changes in time scheduling. Updating the project schedule will be easier at different sources of uncertainty and changing the provisions of the contract.
- Many stochastic conditions such as uncertainty duration, stochastic activity and …that definition of them have many complexities in other existing methods, can be easily assumed in the proposed method of this research.

Based on the results obtained the following suggestions are made for development of the method in future research:

- It has been assumed in this paper that the activities are deterministically performed. Therefore, future research can be improved through assumption of probabilistic networks as well as possibility of loops present in them.
- The RCPSP has been considered in this research as a single-mode problem. Therefore, it can be developed in future studies into the multi-mode version MMRCPSP (Multi-Mode Resource-Constrained Project Scheduling Problem).
- The method proposed in this research was analyzed for a hypothetical example, and its weaknesses and strengths can definitely be analyzed better if employed in a real project.

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