Managing Time and Resources of Construction Projects Using Colored Petri Nets and a Genetic Algorithm

Khodakaram Salimifard
Industrial Management Department
Persian Gulf University
Bushehr, Iran
salimifard@pgu.ac.ir

Gholamreza Jamali
Industrial Management Department
Persian Gulf University
Bushehr, Iran
gjamali@pgu.ac.ir

Sara Behbahaninezhad
Industrial Management Department
Shiraz Payamenour University
Shiraz, Iran
sbehbahani8@gmail.com

***Abstract*—Time and resource management are two crucial activities within the project management framework. This paper demonstrates how resource assignment Petri net (RAPN) a class of colored Petri nets, is applied effectively for modeling and scheduling of construction projects, known as a resource- constrained project scheduling (RCPSP). It captures the dynamic behavior of the project at runtime and enables the decision maker to investigate interactions between resources and project requirements. To determine the most suitable scheduling of project resources, the dynamic population and steady-state ge- netic algorithm (DP–SS GA) is integrated into the modeling framework. It is used to identify the best scheduling plan for different working schemes. In order to illustrate different resource assignment strategies and capture the dynamic inter- actions between resources and activities, a running case study is used. It is found that the modeling framework is capable of capturing the model requirements of a construction project. Compared to the exact solution generated by classic project management tools, the proposed model produced a near optimal solution.**

***Keywords*—Project management, Genetic algorithms, Re- source assignment Petri net, Resource-constrained project scheduling problem.**

I. Introduction

One of the major limitations of project scheduling is re- source constraints, which is considered as a standard problem for project scheduling and is recognized with the title of the resource-constrained project scheduling problem (RCPSP) [1]. It is a well-known scheduling problem where the aim is to optimize an objective under limited resources and activity constraints [2]. Since its advent, the RCPSP has been very popular and has been widely applied in real life industrial scenarios. It is a NP-hard project planning scheduling problem [3].

Traditional project management tools such as program evaluation and review technique (PERT), critical path method (CPM) and Gantt chart tools allow the modelling of sequential and parallel processes in projects and they have been extensively used to graphically represent, monitor, and analyze projects executed over a period of time [4], [5]. Correspondingly, there are many available commercial software packages to accomplish such tasks.

Graphical evaluation and review technique (GERT) and venture evaluation and review technique (VERT) networks are newer models in project management. GERT networks are essentially probabilistic networks that can be used to model uncertainties in the sequence of activities in a project. VERT is a mathematically oriented network-based simulation technique designed to analyze risks existing in three parameters in new projects or ventures, including time, cost, and performance [6]. Based on the studies which referred below and focused on these tools and methods, it has been concluded that traditional techniques for project modelling do not incorporate some fac- tors that are essential for resource planning and management [7] as following:

1) Although these have been successful in offline planning and scheduling, it is difficult to dynamically monitor and control the progress of the project and to model resource constraints because information is loosely coupled [8]– [10].
2) Nonautomatic rescheduling of activities
3) Non-suitability in resolving conflicts arising from resource priorities
4) Incapability of representing resource interdependencies [4]
5) Lack of provision of information to analyze reasons for the tardy progress of activities and
6) Lack of help in the studies of partial allocation, mutual exclusivity, and substitution of resources [6], [8], [11]

Considering the items mentioned above, the need for the establishment of a new project management model with the ability to define features accurately, encourage efficient communications between all the parties involved in the planning and execution of the project, and yield positive results, has been recognized [12]. So, Petri nets can incorporate these factors, and can thus provide a powerful methodology for resource allocation in projects [6].

The object of this paper is to illustrate the resource assignment Petri net (RAPN) modeling and show how a construction project can be built by these elements. So, a practical example named Valfajr project was applied, which represented an RCPSP problem. This project has already been implemented by traditional methods. The dynamic population and steady- state genetic algorithm (DP–SS GA) proposed by Cervantes et al. (2008) [13] was acquired to identify a near optimal solution for scheduling and reusable resource allocation in projects. For this purpose, it was coded in MATLAB software. As a consequence, results obtained from DP-SS GA solving problem showed us that traditional methods were inappropriate to assign resources effectively.

The paper has been organized as follows: In Section II; we review the literature regarding the use of Petri nets in project management. In Section III; our case study is introduced and modeled by RAPN and also DDP–SS GA is described briefly to solve the presented problem. In Section IV; the elicited MATLAB results from the use of this algorithm are discussed. Finally, in Section V; the concluding remarks are outlined.

II. LITERATURE REVIEW

Based on historical perspectives, the concept of the Petri net has its origin in Carl Adam's Petri net dissertation that was submitted in 1962 [14]. In addition to this work, Murata presented in 1989 [15] a brief review of the history and the ap- plication areas of Petri nets. Petri nets have been successfully and extensively applied in the areas of performance evaluation, communication protocols, legal systems, and decision-making models. Project management has also been identified as a prospective area where the modeling power of Petri nets can be used in the dynamic representation and online monitoring of activities and resources, which have been proven very helpful throughout all the phases of management. Many researchers have attempted to use Petri nets as a management tool. Mazzuto and Bevilacqua [7] applied timed colored Petri nets in the project management area in resource assignment for a better project scheduling. Chen and Shan [9] introduced Peti nets as a powerful tool to model, simulate and analyzed a construction project. Lin and Dai [5] applied Petri net theory in the modeling and analyzing complicated projects with multiple resource constraints. Villafa´n˜ez et al. [16] pre- sented a novel algorithm to solve the multi-project scheduling problem with resource constraints (RCMPSP). Bevilacqua et al. [17] described a new approach for a project named timed colored Petri nets (TCPNs). They found that this tool allowed gathering more reliable information for project scheduling and controlling and usefully captured for this field.

III. METHODOLOGY

A. Modeling the Valfajr Project using Colored Petri Nets

In this study, the construction and installation of metal skeletons of the residential-commercial Valfajr Project witheleven units are presented. The project was constructed in Bushehr and had a 200 M^2 area. All its activities were divided into three main categories, including excavation, foundations, and construction and installation of metal skeleton operations. Each of them had a subset of activities. Excavation operations involved excavation mapping, automated excavation, manual excavation, and leveling and tuning. Foundation operations contained foundation mapping, framework, lean concrete, reinforcement, and concrete placement. The reinforcement function consisted of bending and cutting operations and installation. Construction and assembly of the skeletons and their installation were considered in the third category. Table 1 shows data that include the activity names, their predecessors, the precedence relationships, durations, and their usable resources.

TABLE I. ACTIVITIES DATA OF THE PROJECT

NO.	*Name*	*Predecessors*	*Precedence relationships*	*Duration*	*n Usable resources*
1	Excavation mapping	–	–	9	Labor, surveyor surveying camera
2	Automated excavation	1	–	34	Labor, truck
3	Manual excavation	2	–	6	Labor
4	Leveling and tuning	3	–	4	Labor
5	Foundation mapping	4	–	2	Labor, surveyor surveying camera
6	Lean concrete	5	–	8	Labor, truck mixer, 250-grade concrete
7	Bending and cutting armature	1	–	13	Armature worker and armature
8	Armature installation	7,8	–	7	Armature worker
9	Formwork	8	–	17	Labor
10	Concrete placement	9	Activity NO.9 SS +3days	8	Labor, truck mixer, concrete pump, vibrator 350-grade concrete
11	Skeleton construction and assembly	1	–	60	Skeleton work group
12	Skeleton installation	10,11	Activity NO.11 SS+1 day Activity NO.10 SS+7 days	20	Skeleton work group and derrick

After the completion of excavation mapping, the installation area should be smooth. Thus, automated excavation was carried out using six-meter trucks totaling a volume of 120m3 soil per day. In instances where automated excavation could not be used, labor would perform the manual excavation task. Subsequently, leveling, tuning, and foundation mapping were conducted, followed by the pouring of a 250-grade lean concrete on the surface. The reinforcement function consisted of the bending and cutting operation and the installation of armatures, which was executed after concrete was poured. Framework and concrete placement were the activities that followed. They had a precedence relationship o f start–start (SS) with 3 days. It means concrete placement started 3 days after the beginning of the framework (Table 1). For this purpose, mixer trucks, concrete pumps, and vibrator resources should be used for concrete. The vibrator took the air generated by the construction of concrete in the mixer truck. This air reduced the concrete's resistance. The assembly could be performed at the same time as the skeleton was constructed. However, for installation, seven days from concrete placement and one day from construction and assembly had to be elapsed. Activities 11 and 12 were carried out by a group comprising four people. Table 2 lists information about the project resources, including the name of the resource, its type (consumable or reusable), and the maximum number of these resources in a period of time and their scales.

TABLE II. RESOURCE DATA AVAILABLE IN PROJECT

NO .	*Name*	*Consumable / reusable*	*Maximum amount*	*Scale*
1	Labor	Reusable	13	Perso
2	Surveying	Reusable	1	Devic
3	Surveyor	Reusable	1	Perso
4	Truck	Reusable	4	Devic
5	Mixer truck	Reusable	3	Devic
6	Armature	Reusable	5	Perso
7	Concrete pump	Reusable	1	Devic
8	Vibrator	Reusable	2	Devic
9	Derrick	Reusable	2	Devic
10	Skeleton	Reusable	7	Perso
11	Ironware	Consumable	2000	Ton
12	Armature	Consumable	600	Ton
13	250 grade	Consumable	110	Cubic
14	350 grade	Consumable	600	Cubic

The project network diagram is shown in Figure 1. It was based on an activity-on-arrow (AOA) representation scheme. Arrows represented activities, and the circles were nodes representing the start and finish points of these activities. In it, the activity name and the activity duration were specified on and under of each arrow in respectively.

In network diagrams, the precedence relationships and re- sources cannot be shown in an integrated manner. In RAPN which is proposed by Chen et al. [18], a place is shown as a circle, while a line bar represents a transition. A place can be connected to a transition and vice versa. Two nodes of the same type cannot be connected directly. The connection of two nodes is illustrated using an arrow.

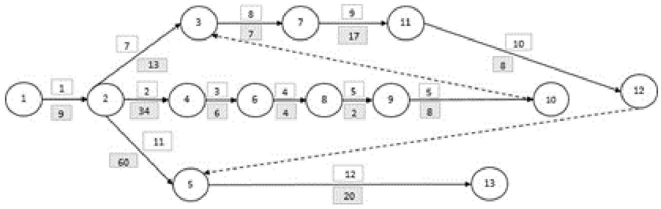

Fig. 1. Network diagram of the Valfajr project

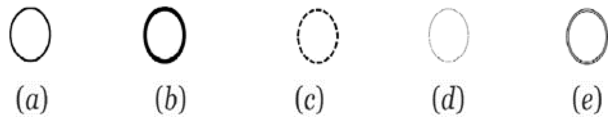

Fig. 2. Node of (a) activity, (b) resource, (c) waiting, (d) delay, and (e) final place.

Therefore, we mapped the above diagram to a RAPN in Figure 3. In Figure 3, a transition is named as Tn, where n is an integer, used to distinguish different transitions. Each place is named according to its type, for example, WP1 is the waiting place number 1, and FP is the final place and Fbeg is the starting place of the model. Each activity n of the project is modeled using two places WPn and APn, where WPn and APn represent the activity place and waiting place, respectively. A delay is modeled using a DP place. Each place is associated with a time attribute representing the timing issue of the corresponding element.

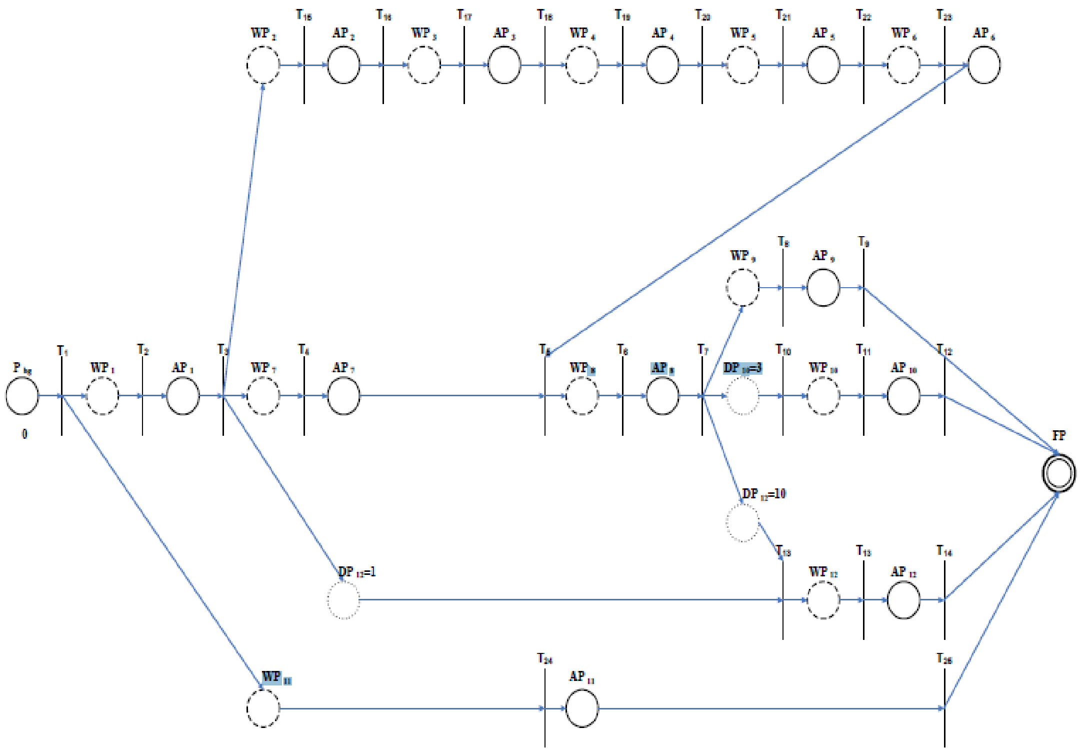

Fig. 3. RAPN model of the Valfajr Project

Resources are divided into two categories: consumable (e.g., parts and materials), and reusable resources (e.g., human and devices). A resource can be shared by multiple activities with random or deterministic assignment strategies. The random as- signment strategy assigns shared resources among competing activities in a random manner. Conversely, the deterministic assignment strategy allows users to explicitly assign resources to specific activities according to decision functions. In RAPN, the activity sharing resources do not need to have temporal relationships [18]. As shown in Table 3, there are three categories of resource sharing scenarios between any two activities, namely, sharing nothing, sharing resources without temporal relationships, and sharing resources with temporal relations [18].

TABLE III. CLASSIFICATION OF RESOURCE ASSIGNMENT BETWEEN TWO SPECIFIC ACTIVITIES [18]

Without sharing		*Consumable resource*		*Reusable resource*	
		Pattern1		*Pattern2*	
Sharing	Types of resource sharing	Random	Deterministic	Random	Deterministic
	Without temporal relations	Pattern 3	Pattern 4	Pattern 5	Pattern 6
	With temporal relations	Pattern 7	Pattern 8	Pattern 9	Pattern 10

In general, we designed the following Table 4 for the case study. In this table, we showed the type of resources, its potential use (consumable or reusable), and the type of patterns used in modeling. Subsequently, one resource of Skeleton working group was assumed to described as below:

Skeleton working group: There were two skeleton working groups and seven persons involved in total. Although one of these groups was a complete group, the other consisted of three persons. Individuals with different expertise were chosen for each group. The adopted strategy was deterministic without temporal relations, and the modeling approach was assumed to follow pattern 6 (as shown in Figure 6). Transitions $RRT_{FrameWorker}$ and $RDT_{FrameWorker}$ represent resource (frame worker) release and resource dispatch, respectively.

TABLE IV. STRATEGIES USED FOR RESOURCE ASSIGNMENT BETWEEN VALFAJR PROJECT ACTIVITIES

NO.	*Type of resources*	*Consumable / reusable*	*Related activities*	*Selected pattern*
1	Labor	Reusable	1,2,3,4,5,6	6
			9,10	10
2	Surveying camera	Reusable	1,5	6
3	Surveyor	Reusable	1,6	6
4	Truck	Reusable	2	2
5	Mixer truck	Reusable	6,10	6
6	Armature worker	Reusable	7	2
7	Concrete pump	Reusable	10	2
8	Vibrator	Reusable	10	2
9	Derrick	Reusable	12	2
10	Skeleton worker	Reusable	11,12	6
11	Ironware	Consumable	11	1
12	Armature	Consumable	7	1
13	Concrete(with 250 grade)	Consumable	6	1
14	Concrete(with 350 grade)	Consumable	10	1

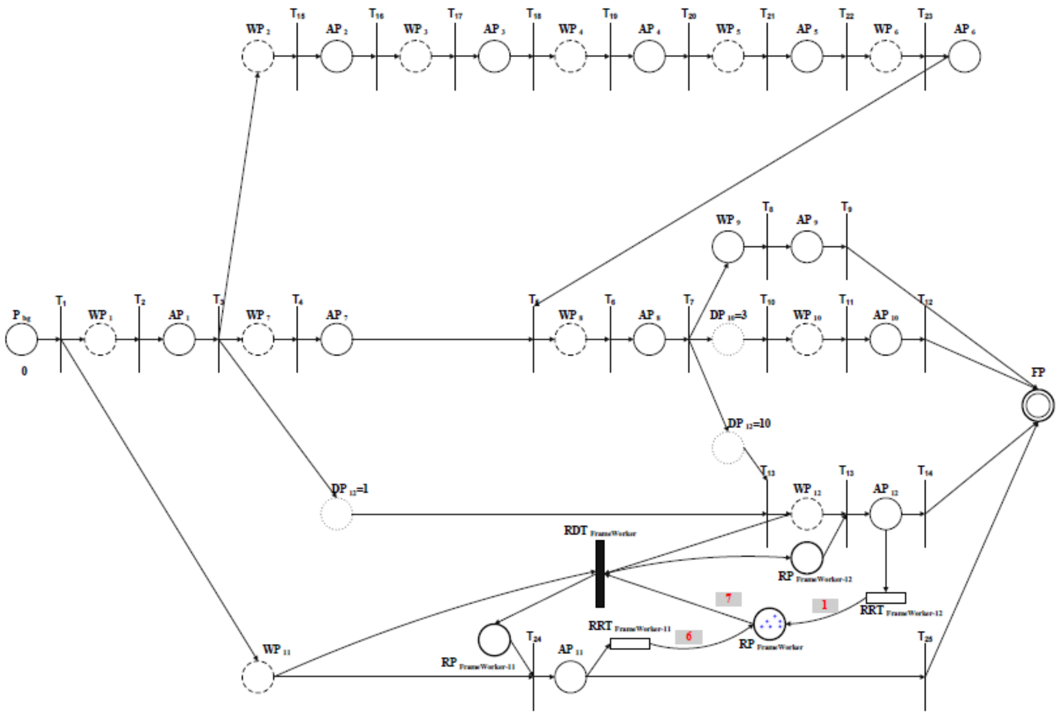

Fig. 4. Skeleton work group assignment in the Valfajr Project

B. Dynamic Population and Steady State Genetic Algorithm

According to Kolisch and Hartmann, the GA is one of the well-known metaheuristic paradigms which are capable of learning. The GA was inspired by the process of biological evolution, a concept that has been introduced by Holland in 1975. In contrast to the local search strategies, a GA simulta- neously considers a set or population of solutions instead of a single solution. Having generated an initial population, new solutions are produced by mating two existing ones (crossover) and/or by altering an existing one (mutation). After producing new solutions, the fittest solutions "survive" and make up the next generation, while the others are deleted. The fitness value measures the quality of a solution, usually based on the objective function value of the optimization problem to be solved [19].

In this study we applied DP–SS GA proposed by Cervantes et al. in [13]. The results of the GA show that it elicits an excellent performance when compared against the top five heuristic-based algorithms published and reported by Kolisch and Hartmann [20], in accordance to elicited results obtained from 1,000 schedules. In the DP–SS GA, the activity list (AL) representation was used and the priority rule was based on combined priority rules and schedule generation schemes (SGS). Two different schemes can be distinguished: the serial schedule generation scheme (S–SGS) and the parallel schedule generation scheme (P–SGS). Both SGS generate feasible schedules that are optimal [21]. Furthermore, the algorithm used the standard two-tournament selection operator and the two-point crossover operator. It applied a steady state strategy for replacement with a dynamic population size. Our case study had a small size, and according to Hartmann in 2002 [22] the initial population size was assumed to be equal to 30.

IV. Results and Discussion

The DP–SS GA algorithm ran in MATLAB environment and began with the initial population of 30 chromosomes. After 300 generations, the amount of fit was fixed and reached the stop criteria. The result obtained from this algorithm was a chromosome scheduled by the P–SGS algorithm and with the following AL:

AL NearOptimal =< 1, 7, 2, 11, 3, 4, 5, 6, 8, 9, 10, 12, P – SGS]. The makespan obtained from this chromosome was 115. This means that if these AL activities had been used and resources were allocated accordingly, the project would have been completed in 115 days.

Indeed, DP–SS GA simulates the Valfajr project. Based on the results obtained from the P–SGS algorithm, 10 steps can be executed to perform project activities. At each stage, one or more activities are performed, based on the results obtained from the decoding of the P–SGS, as indicated in Table 5. This table outlines the 10 stages of decoding P–SGS, the number of ongoing activities, the number of activities carried out, and the types of resources used for each step.

TABLE V. Decoding steps of the Optimal AL and the types of resources used in each step

Stage of allocation re-sources	Number of ongoing activities	Number of activities carried out	Type of resources used
1	1	—	labor
2	7,2,11	1	labor, truck
3	2,11	1,7	labor, truck
4	3,4,5,11	1,7,2	Labor, surveying camera, surveyor
5	6	1,7,2,11,3,4,5	Labor, mixer truck
6	8	1,7,2,11,3,4,5,6	Armature worker
7	9	1,7,2,11,3,4,5,6,8	labor
8	10	1,7,2,11,3,4,5,6,8,9	Labor, mixer truck, concrete pump, vibrator
9	12	1,7,2,11,3,4,5,6,8,9,10	Derrick, skeleton work group
10	—	1,7,2,11,3,4,5,6,8,9,10,1	2 —

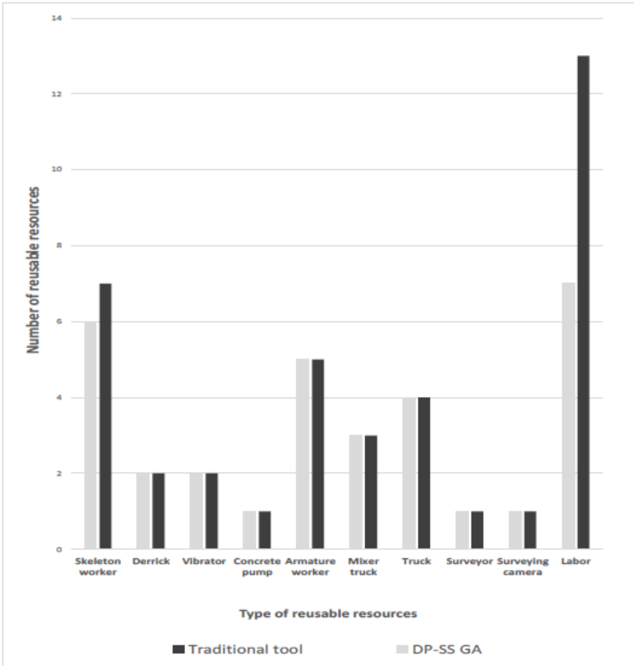

Fig. 5. Resource allocation comparison

According to the obtained results, the resources used in this project are analyzed below:

Labor: They were used in the AL Near O0ptimal activities 1, 2, 3, 4, 5, 6, 9 and 10. The maximum use of labor during the executive process included 7 people out of 13. Indeed, six of them were not used effectively. This would impose additional expenses to the project within 115 working days. Therefore, if the project had not been completed, the project manager would have allowed the maximum number of workers to be equal to seven. Surveying camera, surveyor, mixer truck, armature and skeleton working group: It seems that one surveying camera and one surveyor were enough for the project. This was the same for the mixer truck and armature worker. However, for the skeleton group, one group was useless and additional expenses were imposed. Therefore, the six-worker group was optimal. As a result, only two resources of labor and skeleton working groups were not assigned properly Figure 7).

If the project activities had been scheduled on the basis of the DP–SS GA results, the surplus costs owing to the inefficient use of resources would have been reduced.

V. CONCLUSION AND SCOPE FOR FUTURE RESEARCH

This paper showed how a RAPN used for modeling a construction project and demonstrated its power to visualization. The researcher mapped an AOA network graph to a RAPN network. RAPN is a type of colored Petri net that works better in modeling owing to various features, such as synchronization, resource substitution, and resource conflicts, compared to traditional project management methods. In this method, the user was able to apply various resource allocation strategies and assess the interaction between the resources themselves and the resources and activities in an integral and visual manner. The DP–SS GA also considered these interactions while it solved the problems. In addition, this approach was able to model the project dynamically. Because the project was not affiliated with the graphic representation of activities, contrary to what is depicted in the network diagram, different results could be obtained with the same constructed model. In this study, in order to demonstrate the efficiency and effectiveness of the model, the construction and installation of the metal skeletons of the residential-commercial Valfajr project were modeled. Allocation strategies of reusable resources were also mentioned. As it has stated already, nowadays, even the best optimization procedures are unable to identify the optimal makespan of resource-constrained projects with more than 20 activities and 3 modes in a reasonable computational time. Consequently, for this category of issues, metaheuristic methods, including the genetic algorithm, are appropriate. However, the reason for choosing DP–SS GA is because it was compared to the four best metaheuristic methods in Cervantes et al.in 2008 and provides the best answer. By searching various scientific databases, few prior studies used these two methods together. Therefore, little is known in this area. In future work, by changing some of the genetic operators of DP–SS GA, such as displacement, the genetic algorithms can reduce the number of generations and increase the speed of achieving a near-optimal solution. Moreover, currently, there is no software available for modeling and optimizing RAPNs. Correspondingly, future work is recommended to focus on the design of a professional software to accomplish this task.

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NOMENCLATURE

AL	activity list
AOA	activity-on-arrow
CPM	critical path method
DP-SSGA	dynamic population and steady-state genetic algorithm
GERT	Graphical evaluation and review technique
P – SGS	serial schedule generation
PERT	program evaluation and review technique
RAPN	resource assignment Petri net
RCMPSP	multi-project scheduling problem with resource constraints
RCPSP	resource-constrained project scheduling
S - SGS	parallel schedule generation
SGS	schedule generation schemes
SS	start–start
TCPNs	timed colored Petri nets
V ERT	venture evaluation and review technique