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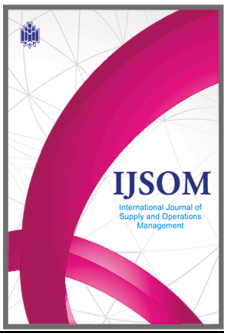

The Combinatorial Multi-Mode Resource Constrained Multi-Project Scheduling Problem

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Abstract

This paper presents the formulation and solution of the Combinatorial Multi-Mode Resource Constrained Multi-Project Scheduling Problem. The focus of the proposed method is not on finding a single optimal solution, instead on presenting multiple feasible solutions, with cost and duration information to the project manager. The motivation for developing such an approach is due in part to practical situations where the definition of optimal changes on a regular basis. The proposed approach empowers the project manager to determine what is optimal, on a given day, under the current constraints, such as, change of priorities, lack of skilled worker. The proposed method utilizes a simulation approach to determine feasible solutions, under the current constraints. Resources can be non-consumable, consumable, or doubly constrained. The paper also presents a real-life case study dealing with scheduling of ship repair activities.

Keywords: Resource Constrained Project Scheduling; Mathematical Formulation; Discrete Event Simulation; Decision Support System.

1. Introduction

Project scheduling consists of determining start times for all tasks such that temporal and/or resource constraints are satisfied and a given objective is optimized (Józefowska and Weßglarz, 2006). It is a complex planning activity, since real-world environments involve the management of multiple projects, with several tasks competing for limited resources (e.g., skilled or unskilled labor, capital, equipment, facilities), shared within a project and with other projects.

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In addition, human resources have multiple skills and the skill levels vary significantly. Real projects are also dynamic in nature due to changes in scope and customers' requirements, adding complexity to the planning problem.

Significant amount of research has been conducted on allocating limited resources to competing tasks and several researchers are actively engaged in addressing different aspects of scheduling issues (Beşikci et al., 2014, Vanhoucke, 2013; Naber and Kolisch, 2014; Xu and Feng, 2014]. Bulk of this research falls under the general area of Operations Research (OR). The literature classifies various scheduling problems as Resource Constrained Project Scheduling Problem (RCPSP), Multi-Mode Resource Constrained Project Scheduling Problem (MRCPSP), Resource Constrained Multi-Project Scheduling Problem (RCMPSP), Resource Constrained Project Scheduling Problem with flexible resource profile (FRCPSP), and Multi-Mode Resource Constrained Multi-Project Scheduling Problem (MRCMPSP).

Abrantes and Figueiredo (2015) worked closely with industrial partners and brought strong empirical evidence that resource constrained project scheduling is indeed a concern in organizations driven by projects. They presented the challenges in to resource management for real-life multiple-projects contexts, characterized by high dynamism and complexity. Resource constrained project scheduling methods have received large attention in the academic literature, however approaches to support organizations are still not established according to the authors. Within the context of project scheduling, modelling of real world situations is a challenging task. Araúzo et al (2010) stated that classical methods, based on mathematical programming, could help decision making when problem complexity is low and the system is somewhat static. On the other hand, these characteristics are seldom true in real world projects. Standard project scheduling software packages present shortcomings on relevant issues in some contexts. For instance, they do not guarantee accuracy in results when tasks require multiple resources that have different calendars associated with them. Faulty interpretations in calculating finish time for tasks exist. They do not support multiple task modes (i.e., only one set of resources for each task). They lack an efficient and automatic resource allocation procedure; they simply adopt fixed standard rules for levelling all resources in a context where rules may differ among the departments of an organization. These shortcomings were the motivation to develop a new approach.

This paper presents a new and general extension of the RCPSP. It is called the Combinatorial Multi-Mode Resource Constrained Multi-Project Scheduling Problem (CMRCMPSP). The mathematical model for the new RCPSP extension is formulated. A real-life case study is presented and solved by a simulation approach. Some discussions on resource utilization and non-renewable resource shortage are also presented as outcomes for the case study.

2. Literature review

Many studies have been carried out in the area of resource constrained project scheduling. Pritsker et al. (1969) introduced the RCPSP, assuming a single task-resource requirements pair. Several variations of the RCPSP methods have since been proposed. Brucker et al (1999) introduced the notion of limited renewable and non-renewable resources and conflicts between multiple resources. Relevant works in the literature that deal with non-renewable resources can be found in Belkaid et al. (2013), Belkaid et al. (2016), Belkaid et al. (2016), Carlier et al. (2016), and Lee et al. (2013). Hartmann and Briskorn (2010) also provided an extensive survey of variants and extensions of the RCPSP method and described solutions for regular and non-regular measures of performance. Bianco and Caramia (2013) developed an exact formulation for RCPSP. Vanhoucke (2013) formulated RCPSP mathematically to minimize the total project duration time by minimizing the start time of the last task, subject to precedence relations among the activities and limited resources. Siu et al. (2015) utilized integer programming technique to plan an upgrade of an existing oil refinery facility, which included reactors, regenerators, and an overhead system. Other authors such as Drexl et al. (2000), Fundeling and Trautmann (2010) and Bouleimen and Lecocq (2003) have also proposed alternatives to RCPSP.

The MRCPSP, an extension of the RCPSP, was introduced by Elmaghraby (1977). The difference between RCPSP and MRCPSP is that the former has only one pair of task duration-resource requirements to perform a task, whereas in MRCPSP each task can be performed by selecting one out of many different combinations of task duration-resource requirements. The various alternate combinations are called modes. Naber and Kolisch (2014) described mode as “a non-pre-emptive, constant resource usage of task over its entire predetermined fixed duration”. Other authors such as Alcaraz and Maroto (2003), Kolisch and Drexl (1997), Jozefowska et al. (2001), Sabzehparvar and Seyed-Hosseini (2008), and Peteghem and Vanhoucke (2010) have proposed both heuristic and exact solutions for MRCPSP.

The RCMPSP, another extension of RCPSP, supports problems where multiple projects compete for the same resource. In RCMPSP, there is only one possible task duration-resource requirement pair (one mode), as in RCPSP. However, RCMPSP works with several projects simultaneously, under precedence and resources constraints. Browning and Yassine (2010) implemented RCMPSP by revising the priority rules. Xue et al (2010) used the neural network approach to solve RCMPSP. Zhang and Sun (2011) utilized priority-rule based heuristics. Laslo and Goldberg (2008) identified uncertainty in the multi-project environment. Chen and Shahandashti (2009) used simulated annealing and Araúzo et al. (2010) applied Multi-Agent System (MAS) approach to solve the RCMPSP problem.

Naber and Kolisch (2014) proposed using a Mixed Integer Programming (MIP) model to solve what they termed as FRCPSP. They explained flexible resource profile by an example. That is, if a given task requires 10 person-days, it may be allocated as a constant profile of 2 persons for 5 days, or as a flexible profile of 3 persons for 2 days, and 2 persons for 2 days. Naber and Kolisch (2014) stated that both exact and heuristic methods need to be further developed in order to handle real-life projects. Other studies on FRCPSP can be found in Baumann and Trautmann (2013) and Ranjbar and Kianfar (2010).

The MRCMPSP approach allows several project tasks to be handled simultaneously, under precedence and resources constraints, and each task can have several modes. Thus far, MRCMPSP represents the largest space search problem cited in the literature. Few research papers address the MRCMPSP (e.g., Speranza and Vercellis, 1993, Xu and Feng, 2014 and Beşikci et al., 2014). Xu and Feng used the modified particle swarm optimization algorithm as a heuristic method to manage construction of a large-scale hydropower plant. They affirm that exact methods are not able to solve complex real world problems and highlight the gap between research and practice, in the area of project scheduling.

Rehm and Thiede (2012) conducted a survey on project scheduling methods and showed that several solutions have been proposed since 1981. A surprising finding of their survey was that the majority of the proposed methods were limited to 51 tasks. The overall objective is to minimize total project duration time. Most methods lack the capability to deal with multiple resource constraints and do not focus on the dynamic nature of the problem.

3. The Combinatorial Multi-mode Resource Constrained Multi-project Scheduling Problem (CMRCMPSP)

The Combinatorial Multi-mode Resource Constrained Multi-project Scheduling Problem (CMRCMPSP) is a general problem. It covers RCPSP, and its associated extensions such as MRCPSP, RCMPSP, and MRCMPS. The choice of representation of a problem impacts its complexity and the search space (schedule options). A very specific representation significantly reduces the size of the search, and works on only a single problem instance. Nonetheless, a general representation, allows for more types of problems to be solved at the expense of searching a larger space.

The MRCPSP and MRCMPS can be performed by selecting one out of several different combinations of resource requirements (modes). The proposed method allows for unlimited modes. It first attempts to assign the required resources in the first mode (mode 1) for tasks, in case a required resource of mode 1 is not available, then it attempts to assign the required resources of mode 2, this logic is applied to all modes. Ultimately, if no resource requirements are met for at least one mode out of the possible set of modes of a given task, then it must wait until a resource becomes available to satisfy at least one mode. The sequential mode order allows project manager to assign ranks to different modes. The multiple modes flexibility covers the concept of resource-driven task duration defined in Wongwai and Malaikrisanachalee (2011), where tasks can start with partial resource requirements fulfilment. In the proposed method, a given task can have several modes, one of them may represent the least resource requirements to start a task.

Depending upon the application, the mode order may represent quality, speed, cost, etc. Project manager can define number of modes for each task according to current needs. Mode durations are independent of resource requirements by other modes. For instance, if mode 1 requires more resources in comparison of other modes, does not imply that duration of mode 1 will be shorter, it may be longer or shorter depending upon the process. Less equipment or fewer labors may work more efficiently than several other equipment or labors. Multiple modes provide additional flexibility in developing project schedules.

Many researchers have worked on several variations of the RCPSP such as RCMPSP and MRCPSP. The case of Multi-mode Resource Constrained Multi-Project Scheduling Problem (MRCMPSP) has not been addressed adequately due to its size and complexity. This research extends the MRCMPSP by proposing a new and general extension of all the aforementioned extensions of the RCPSP. The Combinatorial Multi-Mode Resource Constrained Multi Project Scheduling Problem (CMRCMPSP) is created. The proposed CMRCMPSP modelling is capable to solve RCPSP, RCMPSP, MRCPSP, and MRCMPSP. Recall that MRCMPSP is the general extension of RCPSP found in literature and it allows several project tasks to be handled simultaneously, under precedence and resources constraints, and each task can have several modes. The Figure 1 shows one project with 6 tasks with start node (ST) and end node (EN) for illustrative purposes. Each task can have multiple modes, e.g., task 3 has 3 modes. Task 3, mode 1 requires resources R1 and R2 and task 3's duration under this mode is 7 units of time. Task 3, mode 2 requires resources R2 and R3 and task 3's duration under this mode is 8 units of time. Task 3, mode 3 requires resources R1 and R4 and task 3's duration under this mode is 10 units of time.

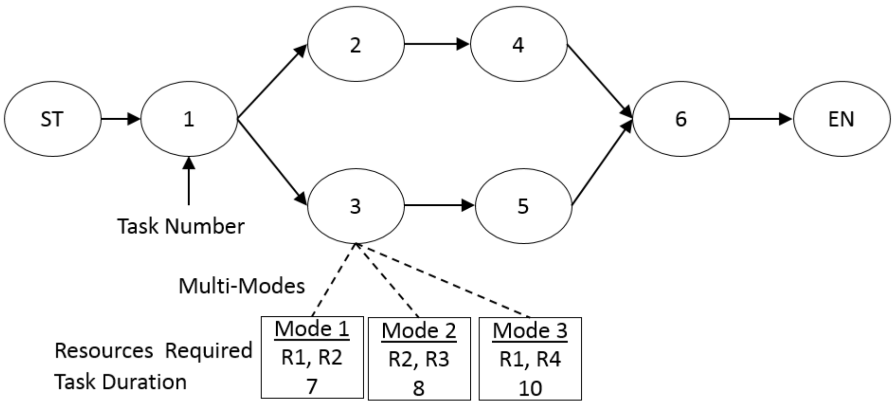

Figure 1. Task on Node of MRCMPSP model

CMRCMPSP allows several project tasks to be handled simultaneously, under precedence and resources constraints, and each task can have several modes. In MRCMPSP and CMRCMPSP each task can be performed by selecting one out of several different modes. However, CMRCMPSP differs from MRCMPSP, because a mode in CMRCMPSP is no longer a set of resources only, but it is a set of combinatorial subsets of required resources capable of executing a given task. In order to illustrate how CMRCMPSP differs from MRCMPSP a small example is shown in the Figure 2. It shows one project with 6 tasks along with start node (ST) and an end node (EN). Each task can have multiple modes, e.g., task 3 has 2 modes, and mode 1 requires 2 welders, 3 cutters, R12, and nonrenewable resource R15. Task 3's duration under mode 1 is 10 units of time. Task 3, mode 2, requires 3 welders, 1 cutter, R13 and R15 and the task 3's duration operating under mode 2 is 12 units of time.

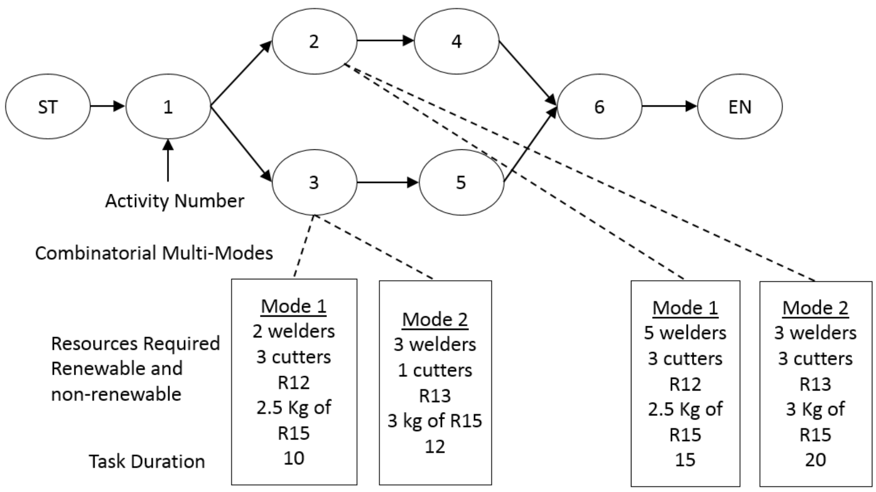

Figure 2. Task on Node of CMRCMPSP model

Table 1 describes resources, their associated skills levels, and their types (renewable or non-renewable). Notice that some resources can have more than one skill associated with them. The set of combinatorial subsets of required resources can be formed with single-skilled resources in CMRCMPSP. The multi-skilled resources are used in this example to adhere to project environment reality. Very few approaches are capable of handling multi-skilled workers.

The various values in the tables categorize skill levels as 1-Excelent, 2- Good, 3-Reasonable, and

4-Poor. For instance, R1 has 3 skills, welding at skill level 1, cutting at skill level 2, and painting at skill level 4. The same logic applies to all other resources. If no skill value is assigned to a resource, it is assumed to have no skills. E.g., resources R12, R13, and R14 are resources that do not have different skills or capabilities, they are resources such as welding equipment, cutting machine, and power generator. Resource R15 (electrode) is the consumable material which is largely used for welding tasks. Resource R15 is identified in this example as non-renewable resource. Last row of Table 1 shows there exist a total of 8 welders, 6 cutters and 6 painters in the resource pool.

Table 1. Resource and Skill

Resources	Welding	Cutting	Painting	Type
R1 (worker 1)	1	2	4	Renewable
R2 (worker 2)	1			Renewable
R3 (worker 3)	1			Renewable
R4 (worker 4)			1	Renewable
R5 (worker 5)		1	3	Renewable
R6 (worker 6)		1		Renewable
R7 (worker 7)	1	2	3	Renewable
R8 (worker 8)	1	2	3	Renewable
R9 (worker 9)	1			Renewable
R10 (worker 10)	1		2	Renewable
R11 (worker 11)	1	2		Renewable
R12 (Machine 1)				Renewable
R13 (Machine 2)				Renewable
R14 (Machine 3)				Renewable
R15 (Electrode)				Non-renewable
Quantity	8	6	6	

CMRCMPSP employs the term combinatorial because it allows for a finite combinatorial number of options to execute tasks. This differs widely from a standard multi-mode approach because number of modes does not define number of different options to perform a task. In the previous extension of multi-mode RCPSP, a given task with two modes has only two options for being executed. However, in the proposed approach, a task with two modes, as it will be shown, can provide more than two options. In Figure 2, Task 3, Mode 1 requires 2 welders out of 8, 3 cutters out of 6, and resources R12, R15. Task 3, Mode 2 requires 3 welders out of 8, 1 cutter out of 6, and resources R13, R15. In this research, the combinatorial mode is defined as a set of combinatorial subsets of required resources. Task 3, Mode 1, the 2 welders required is the first subset, the 3 cutters is the second subset, and so on so forth. For each required subset, a search among a combinatorial number of resources is described by equation 1:

$$\binom{n}{p} = \frac{n!}{(n-p)!\,p!} \qquad (1)$$

Equation 1 provides p combinations of n elements, where p is the required quantity of resources with a given skill and n is the available quantity of resources in the resource pool capable of meeting the required skill. In the above example, Task 3, Mode 1 requires 2 welders out of 8, 3 cutters out of 6, R12, and R15. Task 3, Mode 2 requires 3 welders out of 8, 1 cutter out of 6, R13, and R15. There are a total of 896 different ways to perform Task 3, not just 2. Equation (2) shows the number of alternative combinations for welders in Mode 1:

$$\binom{8}{2} = \frac{8!}{(8-2)!\,2!} = 28 \tag{2}$$

Equation (3) shows the number of different combinations for cutters in mode 1. There are $\binom{8}{2}\binom{6}{3} = 560$ different sets of resources that can perform Task 3 in Mode 1.

$$\binom{6}{3} = \frac{6!}{(6-3)!\,3!} = 20 \tag{3}$$

Equation (4) shows the number of alternative combinations for welders in Mode 2. Equation (5) shows the number of different combinations for cutters in Mode 2. There are $\binom{8}{3}\binom{6}{1} = 336$ different sets of resources that can perform Task 3 in Mode 2.

$$\binom{8}{3} = \frac{8!}{(8-3)!\,3!} = 56 \tag{4}$$

$$\binom{6}{1} = \frac{6!}{(6-1)!\,1!} = 6 \tag{5}$$

Therefore, there are (560 + 336) 896 alternate ways to perform Task 3. A general equation for calculating the number of options to perform a task in the CMRCMPSP is given by equation 6.

$$\sum_{m \in M_{i,j}} \left(\prod_{c \in C_{i,j,m}} \frac{n!}{(n-p)!\,p!} \right) \tag{6}$$

For the above example, for Mode 1, the number of combination of welders and cutters is given by$\binom{8}{2}\binom{6}{3} = 560$, whereas for Mode 2 the number of combination of welders and cutters is given by$\binom{8}{3}\binom{6}{1} = 336$.

$\mathrm{m} \in \mathrm{M}_{1,3} = \{\text{Mode 1}, \text{Mode 2}\}$

$\mathrm{c} \in \mathrm{C}_{1,3,1} = \{\text{2 welders out of 8, 3 cutters out of 6, R12, R15}\}$

$\mathrm{c} \in \mathrm{C}_{1,3,2} = \{\text{3 welders out of 8, 1 cutter out of 6, R13, R15}\}$

$\mathrm{rn}_{(i,j,m,c)} = \mathrm{rn}_{(1,3,1,1)} = 2;\ \mathrm{rn}_{(1,3,1,2)} = 3$

$$\sum_{m \in M_{i,j}} \left(\prod_{c \in C_{i,j,m}} \frac{n!}{(n-p)!\,p!} \right) = \frac{8!}{(8-2)!\,2!} * \frac{6!}{(6-3)!3!} * 1 * 1 + \frac{8!}{(8-3)!3!} * \frac{6!}{(6-1)!\,1!} * 1 * 1 = 896$$

Current literature does not address the above combinatorial problem.

The problem model

The CMRCMPSP model handles multi-projects, combinatorial multi-modes for tasks, task precedence, and temporal interruption constraints such as idle times and maintenance. Multi-skilled and multiple calendars for resources are also permitted. Figure 3 provides an overview of the CMRCMPSP model. It shows three simultaneous projects (separated by a dotted line). Each task, represented by a node, can have multiple modes, e.g., Task 3 of Project 1 has two modes. Each mode can require subsets of resources as previously described. Resource can be renewable, non-renewable, or doubly constrained. In Figure 3, double circle for Tasks 1 of Project 1 indicates that some work has already been performed on this task and the model considers those.

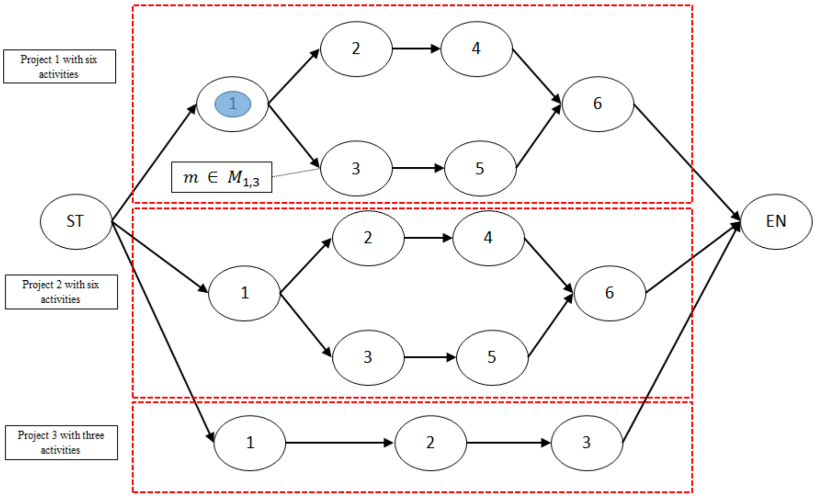

Figure 3. Task on node representation for multiple projects

Mathematical formulation of the CMRCMPSP model

Tables 2, 3, 4, 5 and 6 describe notations for scalar, sets, indices and variables, respectively.

Table 2. Scalars

Scalar	Description
$\mathbf{T}$	interval time, $0 \le t \le T$
$rn_{i,j,m,c}$	Required quantity of renewable resources with skill/capability c operating on mode m for task j of project i
$w_{i,j,m,c}$	Required quantity of nonrenewable resource with capability c operating on mode m for task j of project i
$d_{i,j,m}$	Duration of task j of project v operating on mode m
(i,j,m,c,r)	The 5-tuple (i, j, m, c, r) provides an index $re \in RE$
(i,j,m,c,y)	The 5-tuple (i, j, m, c, y) provides an index $nr \in NR$
$z(Re_{(i,j,m,c,r)}, t)$	= 1 , if the renewable resource r with skill c required, operating on mode m for task j of project i is available at time t based on its own calendar = 0, otherwise
$z(Nr_{(i,j,m,c,y)}, t)$	= 1, if the nonrenewable resource y with capability c required, operating on mode for task j of project i is available at time t = 0, otherwise

Table 3. Continued

Scalar	Description
$dd_{i,j}$	Assigned due date for task j of project i
dd_i	Assigned due date for project i
$c_{i,j}$	Tardiness cost task j of project i per time unit
c_i	Tardiness cost of project i per time unit
$cs_{(sr)}$	Cost associated by using a given skill out of multiples of renewable resource re
cr_{re}	Cost/unit time of renewable resource re in regular time
cro_{re}	Cost/unit time of renewable resource re in over time
crm_{re}	Cost/unit time of renewable resource re in maintenance
cw_{nr}	Cost/unit of nonrenewable resource nr
car_s	Cost for adding a renewable resource with skill s
caw_{nr}	Cost for purchasing one unit of nonrenewable resource nr
$AR_{s,t}$	Quantity of renewable resources available with skill/capability s at time t
$AW_{s,t}$	Quantity of nonrenewable resource with capability s available (on hand) at time t
(i,j,m,c)	The 4-tuple (i,j,m,c) provides an index $s \in S$
$ARD_{s,t}$	Quantity of renewable resources added with skill/capability s at time t
$AWD_{nr,t}$	Total amount of nonrenewable resource nr delivered at time t
$MRD_{s,t}$	Quantity of renewable resources with skill/capability s in maintenance at time t
$TAWD_{nr}$	Total amount of nonrenewable resource nr ordered
$TARD_s$	Total quantity of renewable resources added with skill/capability s
TR_{re}	Total amount of time used of renewable resource re in regular time
TW_{nr}	Total quantity used of nonrenewable resource nr
TRO_{re}	Total amount of time used of renewable resource re in over time
TRM_{re}	Total amount of time in maintenance of renewable resource re
$TC_{i,j}$	Tardiness cost for task j of project i
TC_i	Tardiness cost of project i
$TCS_{(i,j,m,c,r)}$	Cost calculated for choosing a given skill out of multiples of renewable resource re
TCS	Total cost associated of choosing a skill out of multiples for all renewable resources, in all modes, tasks, projects and time.
TCR	Total cost associated of resources, in all modes, tasks, projects and time.

Table 4. Sets

Set	Description
RE	set of renewable resources, $re \in RE$
NR	set of nonrenewable resources, $nr \in NR$
RN	set of resources, $rn \in (RE \cup NR)$
I	set of projects, $i \in I$
$\mathbf{J_i}$	set of tasks of project i, $j \in J_i$
P	set of all precedence relationships
$\mathbf{M_{i,j}}$	set of modes for task j of project i, $m \in M_{i,j}$
$\mathbf{C_{i,j,m}}$	set of skills/capabilities operating on mode m of task j and project i, $c \in C_{i,j,m}$
$\mathbf{R_{i,j,m,c}}$	Set of renewable resources with skill/capability c operating on mode m of task j, and project i, $r \in R_{i,j,m,c} \subseteq RE$
$\mathbf{Y_{i,j,m,c}}$	set of nonrenewable resources with capability c operating on mode m, for task j of project i $y \in Y_{i,j,m,c}$ $Y_{i,j,m,c} \subseteq NR$
S	Set of subsets of renewable resources with same skills or capabilities, $s \in S$
$\mathbf{SRe_{re}}$	Set of skills for renewable resource re, $sr \in SRE_{re}$

Table 5. Indices

Index	Description
i	Project index, $\forall i \in I$
j	Task index, $\forall j \in J_i$
m	Mode index, $\forall m \in M_{i,j}$
c	Subset index, $\forall c \in C_{i,j,m}$
r	Resource index, $\forall r \in R_{i,j,m,c}$
sr	Skill index of a resource, $\forall sr \in SRE_{(i,j,m,c,r)}$
s	Skill index, $s \in S$

Table 6. Variables

Variable	Description
$st_{i,j}$	Start time of task j, project i
$ft_{i,j}$	Finish time of task j, project i
$x_{i,j,m,t}$	= 1, if task j of project i, operating on mode m, is started at time t = 0. otherwise
$h_{i,j,m}$	= 1, if task j of project i is operating on mode m = 0, otherwise
$u_{(Re_{(i,j,m,c,r)},t)}$	= 1, if the renewable resource re with skill c required, operating on mode for task j of project i is available at time t because it is not being used for any other mode among all the projects = 0, otherwise

The mathematical formulation of RCPSP and MRCPSP fall in the class of Mixed-Integer Linear Programming models (MILP), whereas the proposed CMRCMPSP model falls in the class of the Mixed-Integer Nonlinear Programming models. CMRCMPSP is nonlinear due to nonlinear constraints. The CMRCMPSP model can be mathematically described as follows:

$$f = \min((\sum_{i \in I}(TC_i + \sum_{j \in J_i} TC_{i,j}) + TCR + TCS) \quad (7)$$

Subject to:

$$\sum_{m \in M_{i,j}} x_{i,j,m,t} = 1, \forall j \in J_i, \forall i \in I, \text{for all } t \in [0,T] \quad (8)$$

$$x_{i,j,m,t} * t \geq st_{i,j} \ \forall j \in J_i, \forall i \in I \quad (9)$$

$$ft_{i,j} \geq st_{i,j} + d_{i,j,m} \ \forall j \in J_i, \forall i \in I, \forall m \in M_{i,j} \quad (10)$$

$$rn_{(i,j,m,c)} * x_{i,j,m,t} \leq AR_{((i,j,m,c),t)}, \forall i \in I, \forall j \in J_i, \forall m \in M_{i,j}, \forall c \in C_{i,j,m}, \forall t \in [0,T] \quad (11)$$

$$AR_{((i,j,m,c),t)} \leq \sum_{r \in R_{i,j,m,c}} z_{(Re_{(i,j,m,c,r)},t)} * u_{(Re_{(i,j,m,c,r)},t)} \ ,\forall\ i\ \in I, \forall j\ \in J_i\ ,\forall m\ \in M_{i,j}\ ,\forall t\ \in [0,T] \tag{12}$$

$$\sum_{i \in I} \sum_{j \in J_i} \sum_{m \in M_{i,j}} \sum_{c \in C_{i,j,m}} \sum_{r \in R_{i,j,m,c}} u_{(Re_{(i,j,m,c,r)},t)} \leq 1\ ,,\forall t\ \in [0,T] \tag{13}$$

$$\sum_{m \in M_{i,b}} t * x_{i_1,b,m,t} \geq \sum_{m \in M_{i,a}} (t + d_{i_1,a,m}) * x_{i_2,a,m,t}\ ,\forall (a,b)\ \in P, \forall i_1, i_2\ \in I, \quad for\ all \in [0,T] \tag{14}$$

$$TCS_{(i,j,m,c,r)} \geq cs_{(sr)} * x_{i,j,m,t}\ ,\forall\ i\ \in I, \forall j\ \in J_i\ ,\forall m\ \in M_{i,j}\ ,\forall c\ \in C_{i,j,m}\ ,\forall r\ \in R_{i,j,m,c}\ , \forall sr\ \in \mathrm{SRE}_{(i,j,m,c,r)}, \forall t \in [0,T] \tag{15}$$

$$TCS \geq \sum_{i \in I} \sum_{j \in J_i} \sum_{m \in M_{i,j}} \sum_{c \in C_{i,j,m}} \sum_{r \in R_{i,j,m,c}} TCS_{(i,j,m,c,r)}\ \ for\ all\ t\ \in [0,T] \tag{16}$$

$$AW_{((i,j,m,c),t)} \leq \sum_{y \in Y_{i,j,m,c}} z_{(Nr_{(i,j,m,c,y)},t)}\ ,\forall\ i\ \in I, \forall j\ \in J_i\ ,\forall m\ \in M_{i,j}\ ,\forall c\ \in C_{i,j,m}\ ,\forall t\ \in [0,T] \tag{17}$$

$$w_{i,j,m,c} * x_{i,j,m,t} \leq AW_{((i,j,m,c),t)}, \forall\ i\ \in I, \forall j\ \in J_i\ ,\forall m\ \in M_{i,j}\ ,\forall c\ \in C_{i,j,m}\ ,\forall t\ \in [0,T] \tag{18}$$

$$AR_{((i,j,m,c),t+1)} \leq AR_{((i,j,m,c),t)} + ARD_{((i,j,m,c),t)} - MRD_{((i,j,m,c),t)}, \forall\ i\ \in I, \forall j\ \in J_i\ ,\forall m\ \in M_{i,j}\ , \forall c\ \in C_{i,j,m}\ ,\forall t\ \in [0,T] \tag{19}$$

$$AW_{nr,t+1} \leq AW_{nr,t} + AWD_{nr,t}, \forall t\ \in [0,T] \tag{20}$$

$$TCR \geq \sum_{nr \in NR} cw_{nr} TW_{nr} + \sum_{nr \in NR} caw_{nr} TAWD_{nr} + \sum_{re \in RE} cr_{re} TRe_{re} + \sum_{re \in RE} car_{re} TARD_{re} + \sum_{re \in RE} cro_{re} TRO_{re} + \sum_{re \in RE} crm_{re} TRM_{re}, \text{ for all } t \in [0,T] \quad (21)$$

$$TC_{i,j} \geq c_{i,j} * \left(\sum_{m \in M_{i,j}} (t + d_{i,j,m}) * x_{i,j,m,t} - dd_{i,j} \right), \forall i \in I, \forall j \in J_i, \text{for all } t \in [0,T] \quad (22)$$

$$TC_i \geq c_i * \left(\sum_{m \in M_{i,N}} (t + d_{i,N,m}) * x_{i,N,m,t} - dd_i \right), \forall i \in I, \text{for all } t \in [0,T] \quad (23)$$

$$x_{i,j,m,t} \in \{0,1\} \forall i \in I, \forall j \in J_i, \forall m \in M_{i,j}, \forall t \in [0,T]$$

$$u_{(Re_{(i,j,m,c,r)},t)} \in \{0,1\} \forall i \in I, \forall j \in J_i, \forall m \in M_{i,j}, \forall c \in C_{i,j,m}, \forall r \in R_{i,j,m,c} \forall t \in [0,T] \quad (25)$$

$$z_{(Re_{(i,j,m,c,r)},t)} \in \{0,1\} \forall i \in I, \forall j \in J_i, \forall m \in M_{i,j}, \forall c \in C_{i,j,m}, \forall r \in R_{i,j,m,c}, \forall t \in [0,T], AR_{re,t} \in Z^+, AW_{nr,t}\, Q, \forall re \in RE, \forall nr \in NR \quad (26)$$

Objective function given by equation (7) is to minimize the total tardiness over all projects. Constraint set defined by equation (8) ensures that all tasks are scheduled only once by selecting only one mode. Constraint set defined by equation (9) calculates start time for all tasks. Constraint set defined by equation (10) calculates finish time for all tasks. Constraint set defined by equation (11) imposes the maximum quantity of available renewable resource with capability c at time t for any project, task, and mode. Constraints set (12) calculate the maximum level of available renewable resources with capability c at time t according to the parameter z and binary variable u. It is a nonlinear constraints. Constraint set (13) ensures that resources are not assigned for more than one project, task, mode, capability at the same time t. Constraint set (14) reflects the precedence relationships among the tasks of all projects. Constraint set (15) calculates the total cost associated of choosing a capability c of a renewable resources at time t. Resource have multi-skills/capabilities, the first skill of the set (index 1) is the less costly, two is more costly, and so on so forth. This is a non-linear constraint. Constraint set (16) calculates the total cost associated of choosing the capabilities of renewable resources for all time t. Constraint set (17) imposes the maximum level for the nonrenewable resource with capability c usage at time t over all projects. Constraint set (18) imposes the maximum quantity of available nonrenewable resources with capability c at time t for any project, task, and mode. Constraints set (19) calculate the maximum level of renewable resources with skill/capability c at time t according to the sum of the current quantity of renewable resources with skill/capability c at time t and renewable resources with skill/capability c added on time t minus the quantity of renewable resources with skill/capability c on maintenance. Constraints set (20) calculate the maximum level of nonrenewable resources nr at time t according to the sum of the current quantity of nonrenewable resources nr on hand and nonrenewable nr on order delivered on time t. Constraint set (21) calculates the total cost of the general renewable and nonrenewable resources. Constraint set (22) calculates the penalty cost due to tardiness values for each task. Constraint set (23) calculates the penalty cost due to tardiness values for each project. Constraint set (24) specifies the feasible ranges for the decision variables. Constraint set (25) specifies the feasible ranges for the decision variables. Constraint set (26) specifies the feasible ranges for the decision variables.

Typically, resource constrained project scheduling problems are formulated mathematically as an optimization problem, with an objective to minimize total project duration time, subject to a set of resource constraints. Even though the authors recognize many benefits from these techniques, such formulations work for small and medium scale problems with relative low complexity. Maenhout and Vanhoucke (2015) stated as future research in their recent work: “We aim to develop solution techniques that are able to tackle real-life problems. This means that on the one hand, we should increase the problem size (in terms of number of activities) scheduling one or multiple projects. On the other hand, we should expand the problem definition and incorporate additional personnel and task characteristics such as personnel skills, multiple modes of operation for a task, task pre-emption, etc. Exact optimization techniques will not be able to cope with the further extension of the problem definition and size. For this reason, we will focus on (hybrid) heuristic optimization techniques that combine the advantages of both mathematical programming techniques and meta-heuristics optimization”. Due to aforemention issues highlighted by Maenhout and Vanhoucke (2015), a simulation based approach named STREAM (Pinha, 2015) was applied to solve the CMRCMPSP. The case study described in the next section represents a production environment driven by projects which provides all features for the CMRCMPSP.

4. Case Study: Ship Repair and Maintenance

All ships and offshore platforms, however large or small, undergo scheduled or unscheduled repair and maintenance. This industry provides highly customized service and deals with unpredictable demand. Some aspects of ship maintenance, such as cleaning and painting have been automated (Sjøbakk et al., 2013), (Navarro et al., 2013), (Navarro et al., 2011). However, a vast majority of tasks are performed manually. Typical services include: a) Docking, b) Hand scraping, c) High pressure fresh water jet cleaning, d) Painting, e) Tank cleaning, f) Steel work, g) Repair of ship’s structure, h) Repair of propulsion system, i) Piping repair, j) Valve repair, k) Electrical system, l) Undocking, and m) Testing at sea. Project scheduling is difficult due to finite resources, such as docks, cranes, and worker skills and uneven flow of repair orders. Table 7 lists some of the resources, grouped by work teams, machines, tools, and material handling devices (Pinha et al., 2011).

Table 7. Types of Resources

Work Teams	Machines	Tools	Material Handling
Mechanical	Plasma Cutting	Hydro-jet pumps	Forklift
Structure	Pipe bending	Paint pumps	Trucks
Paint	Welding Machines	Hydraulic pumps	Cranes
Sand-blasting	Tube resources	Sand-blasting pumps	Pulley

Docks are the most valuable resources of a repair shipyard, they are expensive and are limited resources. More than one ship can be at dock at a time. It is a favorable business situation, but it complicates the project scheduling. A manager is assigned for each dock. In shipyards, the manager is often responsible of all tasks related to her/his dock. Dock managers are highly skilled and influential. They are rewarded for efficient operation of their docks. A dock manager competes with other dock managers for resources. Such practice often results in optimizing operations at an individual dock, while sub-optimizing the overall organization objectives. Such an approach results in scheduling slippage and cost overruns (Pinha and Ahluwalia, 2013), and (Pinha and Ahluwalia, 2014). When a task is carried out at a shipyard, the necessary resources are sent to the desired location. The ships are static and the resources are brought to them. Key resources at a repair shipyard are the work teams and their tools. The bottlenecks occur not when the teams are working in the resource centers, but when they are working on board the ships, this being the factor that ultimately determines how long a ship remains in dock.

Inputs

Real world data was collected from a shipyard in Rio de Janeiro/Brazil. The shipyard has five docks. A project for repairing a complex vessel is described. It is a class leading ROV (remotely operated underwater vehicle) construction support vessel ideally suited to perform subsea operations across a wide range of water depths and environmental conditions. It is used to repair oil offshore platforms. The project required 111 tasks with 475 multiple skilled resources. Table A.1 in the Appendix describes the required tasks, and their precedence relationship. Table A.2 in the Appendix shows the skills required to repair this ship. The resource requirements for tasks/modes, and the multi-skilled resources are described in Tables A.3 and A.4 respectively in the Appendix.

Results applying STREAM

For this case study two simulations were run. The first simulation run was performed to assess which tasks will be delayed due to lack of resources. The second run utilizes the output of the first run to obtain an improved result. Tables 8 and 9 show waiting times for some tasks. These tasks are waiting for resources which were not available when required. Task 61 was eligible to start on Jun 3, 2015, but 36 units of the nonrenewable resource (electrode ok 4600.1 / 8) were not available on hand. Task 61 was started on Jun 30, 2015. This was the date when a new order quantity of the nonrenewable resource was delivered in the shipyard. Simulation run 1 generates outputs considering the nonrenewable resource issue. Simulation run 2 estimates the impact of non-renewable resource being delivered on Jun 3, 2015.

Table 8. Lack of resources when required (Run 1)

Task	Eligible Date	Start Date	Waiting Time	Qty.	Resources
89	May 18, 2015	June 12, 2015	25.58	1	Fluid Jet
88	May 18, 2015	June 12, 2015	25.54	1	Fluid Jet
82	May 18, 2015	May 19, 2015	1.13	1	Support
84	May 19, 2015	May 22, 2015	3.04	5	Fluid Jet
35	May 19, 2015	June 1, 2015	13.04	14	Fluid Jet
50	May 22, 2015	June 4, 2015	13.08	10	Fluid Jet
43	May 22, 2015	June 3, 2015	11.83	12	Fluid Jet
68	May 28, 2015	June 8, 2015	10.62	1	Valves repairing

Table 9. Continued

Task	Eligible Date	Start Date	Waiting Time	Qty.	Resources
61	**June 3, 2015**	**June 30, 2015**	**26.92**	**36**	**electrode ok 4600.1 / 8**
51	June 12, 2015	June 24, 2015	11.75	7	Painter
21	June 18, 2015	June 19, 2015	0.92	1	Painter

Figure 4 shows the resource utilization for all required resource for repairing the vessel. The colors for bars in the chart represent different skills. E.g., red color bars are for painting, yellow are for plumbing, and so on. The chart provides a clear indication that painters are the resource most utilized. Based on Figure 4, the project manager may consider adding another painter.

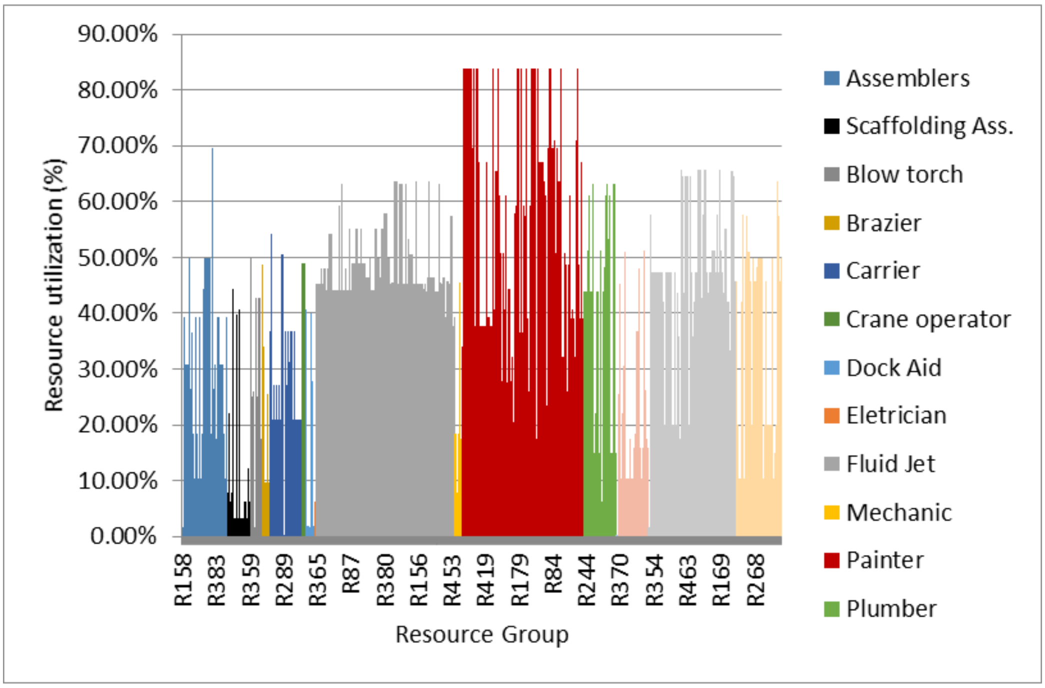

Figure 4. Resource Utilization (Run 1)

Table A.5 shows the individual cost and schedule for all the 111 tasks. Total project cost was estimated as $9,876,833, requiring 70 days for project completion. Figure 5 shows the accumulated cost for tasks. X-axis represents the tasks, which are numbered from 1 to 111. Y-axis represents the accumulated cost associated for performing tasks in millions (USD).

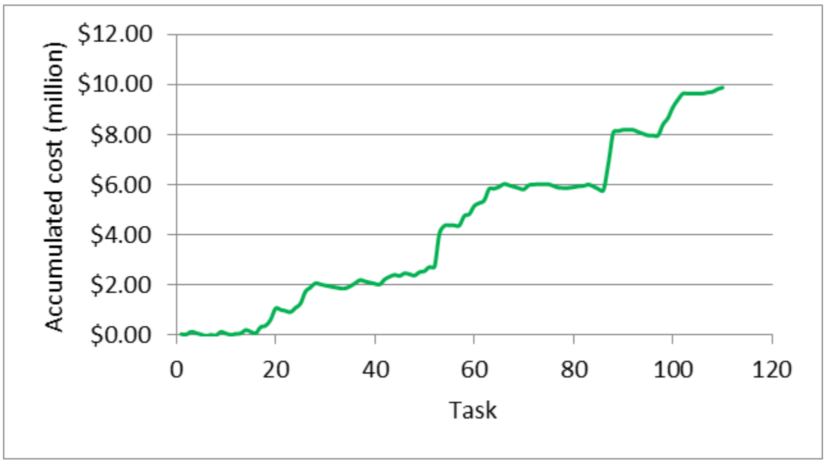

Figure 5. Accumulated Cost with non-renewable issue in Task 61

Figure 6 shows due date deviations. Task 61 requires 12 additional days for completion. Table 9 showed that Task 61 had to wait due to a late delivery of the nonrenewable resource (electrode ok 4600.1 / 8). Thus, the deviation shown in the Figure 6 is caused by the nonrenewable resource. What-if the delivery date for the nonrenewable resource could be moved to Jun 3, 2015, what impact would it have on cost? Simulation run answers this question.

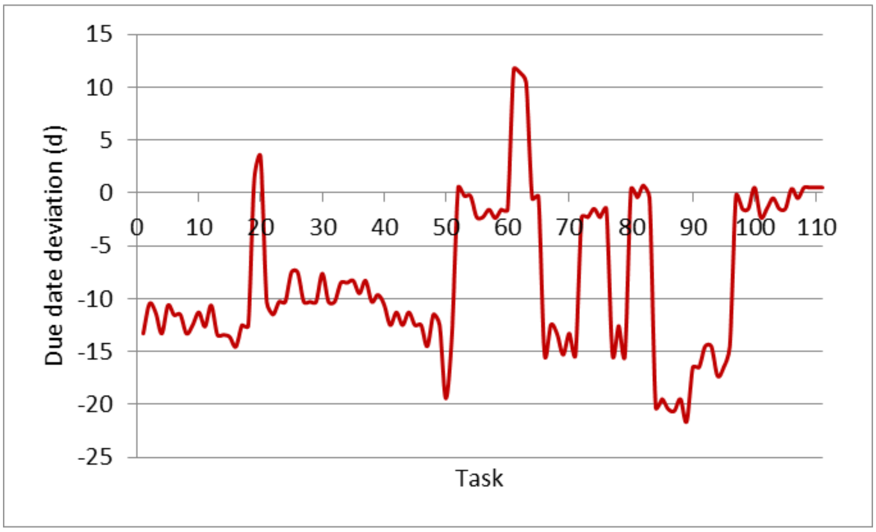

Figure 6. Deviation of Due Dates with non-renewable resource issue

Figure 7 shows the accumulated cost among tasks for simulation run 2. A reduction in cost for Task 61 could be obtained due to reductions in penalty cost associated for this task.

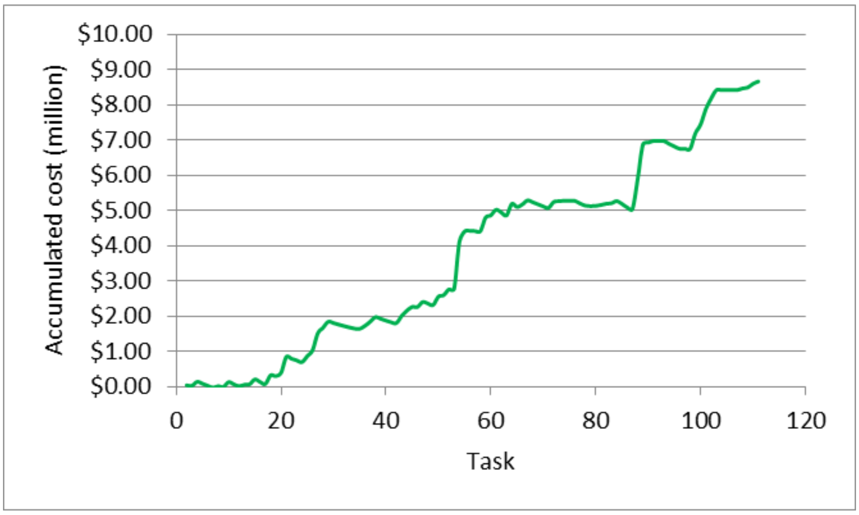

Figure 7. Accumulated cost with earlier deliver date for the non-renewable resource

Figure 8 shows the deviations against tasks due dates after re-planning the delivery date for the nonrenewable resource (Run 2). Task 61 has no longer a positive deviation of 12 days, instead Task 61 finished 14 days earlier than its due date. More than $1,000,000 in cost could be saved and 5 days in project reduction was found by re-planning the nonrenewable resource. Total project cost was reduced to $8,660,104, and total project duration was reduced to 65 days.

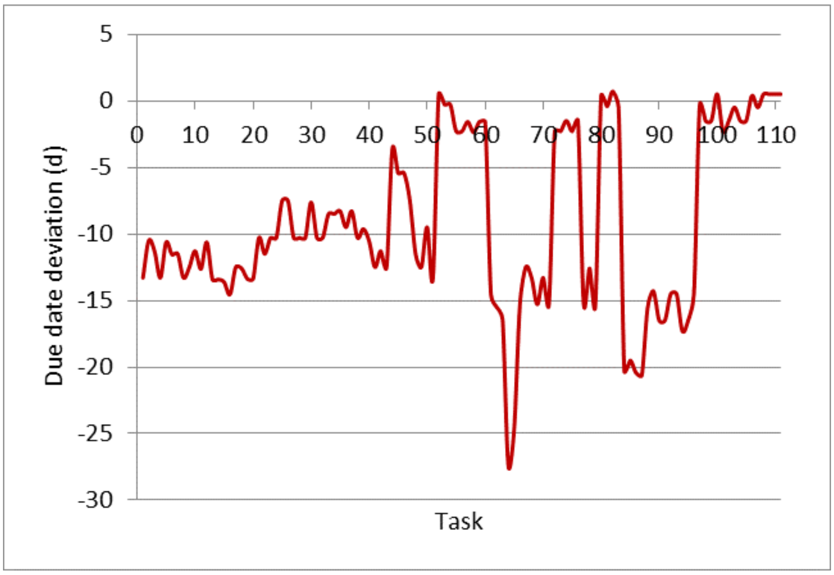

Figure 8. Deviation of Due Dates with non-renewable resource issue solved

5. Conclusions

There are major gaps between project scheduling theory and practice. Many authors (Maenhout and Vanhoucke, 2015), (Abrantes and Figueiredo, 2015), (Coughlan et al., 2015), (Xu and Feng, 2014), (Naber and Kolisch, 2014), (Rehm and Thiede, 2012) have indicated a need to expanded project scheduling methods to meet the needs of "real-world" projects. This research proposes one such extension. It extended the RCPSP methods to handle resources with multiple modes and multiple skills. The extension of the RCPSP is called CMRCMPSP. The overall objective of the method remains the same, that is, minimizing total project duration and cost, subject to resource constraints.

Resource allocation problems are typically formulated mathematically, as an optimization problem, with an objective to minimize total project duration, subject to a set of resource constraints. Such methods attempt to provide a single "optimal" solution. There are many benefits to formulating the program mathematically. However, such formulations do not support large scale project scheduling problems and make several unrealistic assumptions in order to keep the problem mathematically tractable. The methodology used in this research is based on a flexible discrete event simulation, where project manager is an integral part of the resource allocation process. Project manager is provided a software tool called STREAM to provide dynamic decision support and to adapt to changes in resources and priorities.

STREAM allows the development of a project schedule with managerial input, the project manager can evaluate alternate schedules by conducting what if type analysis. It is an iterative process with project manager in the loop. STREAM can provide cost and project duration for each scenario. Managerial decisions refer to actions such as varying material availability (changing release dates and due dates), adjusting capacity levels (altering the maximum number of working hours for specific resources, maintenance of equipment), and authorizing overtime for specific workers.

STREAM also enhances the decision-making process by providing scheduling detail not found in the systems reported in open literature. For instance, the information relative to the task waiting times shown in Section 4, Tables 8 and 9 require matching of multiple resources. This output highlights the tasks that were delayed due to lack of resources. This information permits a timely assessment of possible shortcomings (e.g., the project scheduler may need to renegotiate a supply delivery date to avoid resource shortage).

The proposed methodology was applied to a ship repair project. Regarding the modelling of input data, there is commonly a trade-off between a model's accuracy in capturing the relevant features of the project-planning environment and the resulting model complexity. In this research, alternate ways of performing a task (multi-modes), multiple worker skills levels, renewable and non-renewable resources, were considered. Such issues are common in real-life projects.

STREAM was validated on a project described in the literature (Pinha et al., 2015). It was then applied to the ship repair and maintenance activity carried out at a shipyard in Brazil. STREAM was able to finish the ship repair project in 70 days, with at a cost of $9,876,833. STREAM was able to determine that shortage of a non-renewable resource (electrode ok 4600.1 / 8) delayed task T61 by 26 days. STREAM was able to propose that a change of delivery date of the non-renewable resource could result in reducing the cost to $8,660,104 and project duration to 65 days. STREAM identified that resource shortages are costing more than a million dollars on ship repair project. STREAM was able to solve the problem with 3,000 tasks, 5,000 modes, and 400 multi-skilled resources, in 78 seconds. STREAM also solved a scheduling problem with 10,434 tasks, 15,000 modes, and 400 multi-skilled resources, in 810 seconds, while running 100 projects simultaneously.

6. Contributions and Future Research

This research expanded the existing Resource Constrained Project Scheduling Problem (RCPSP) methodology to include multiple combinatorial task modes, projects, and resource skills. The Combinatorial Multi-mode Resource Constrained Multi-project Scheduling Problem (CMRCMPSP) includes capabilities provided by RCPSP, MRCPSP, RCMPSP, and MRCMPS methods. CMRCMPSP allows for additional constraints and it makes fewer assumptions than the previous methods. It was shown that a task with two modes can be carried out in several ways, as opposed to just two ways. The multiple modes formed by a set of subsets of a resource provides higher flexibility to resource allocation compared with previous approaches. The simulation approach is better equipped to meet real world project needs, as opposed to obtaining an exact solution by mathematical formulation. Simulation can handle: 1) Multiple combinatorial modes for tasks, 2) Multiple skills and capabilities for resources, 3) Multiple priority rules for different resources, and 4) Multiple calendars with interruptions. Current software tools do not provide such capabilities.

The proposed approach could be expanded to include a capability to track and report on task status and resource utilization in near real-time to facilitate its use on a daily basis. Project tracking based on the Earned Value Management (EVM) technique could also be added. Future work could also include linearization of the non-linear problem CMRCPMPSP. Algorithms such as Branch and Cut, Branch and Bound, Column Generation, or Branch and Price, could be developed to verify if optimal solutions can be found and proved for the CMRCPMPSP.

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