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A Decisional Framework for Concurrent Planning of Multiple Projects and Supply Chain Network

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Abstract. This paper studies scheduling of multiple projects under generalized precedence relation between activities and limited availability of resources. The proposed mixed integer model considers two types of the resources including renewable and non-renewable ones. The renewable resources are available in initial quantity at projects' worksites. Nevertheless, it is possible to rent limited supplementary quantity of them over periods in which requirement for the resources may exceed the initial availability. With considering the due-dates that are given for the activities, the assumption makes the model able to decide optimally, either to pay for renting additional resources and not to pay for high penalty costs, or vice versa. In order to satisfy the activities' demand for the nonrenewable resources, it defines a production-transportation plan by planning supply chain which supplies the resources to the projects' worksites. The application of the model is investigated on a use-case from a French project called CRIBA.

Keywords: Generalized Resource Constrained Multi Project Scheduling Problem, Supply Chain Planning, Optimization, Mixed Integer Programming.

1 Introduction

Generalized Resource Constrained Multi Project Scheduling Problem, GRCMPSP, as it is introduced for the first time in [1], is the problem of scheduling multiple projects to minimize makesapn of executing the projects subject to generalized precedence relation of the activities and limited availability of the required resources.

Earliest studies in resources constrained project scheduling problems feature only one type of the resources called renewable resource, [2], [3] and [4]. These resources such as machineries and labor are assumed to be available over time periods of planning horizon in their constant and limited quantity. Extensions of the problem by modification on this assumption is regarded in Time Constrained Project Scheduling Problem, TCPSP, wherein the resources' availability can increase by rent of additional quantities, in order to meet totally a deadline which is determined for end of the project(s), [5] and [6]. In our model we exert the approach of TCPSP while we are imposing a limit for maximum add of supplementary quantities. With considering due-dates that are given for fulfilling each of the activities, the possibility of renting additional quantities makes the model able to avoid paying immoderate cost for accomplishing the activities whose penalty cost is notably greater than the rent cost of additional capacities of the resources.

Besides the renewable resources, dealing with nonrenewable resources such as budget and consumable materials has drawn the attention of the researches in the last decades as well. As the first research study, [7] introduces incorporation of material ordering problem with project scheduling models. It presents a set of algorithms that can be used to calculate the early and late start schedules under the material handling constraints. In a subsequent study, the authors in [8] present a heuristic based on the least slack rule to deal with large scale problems. [9] presents a mixed integer programming model to minimize total cost of scheduling the projects and ordering the materials by defining the optimal values for finish time of the activities and schedules for material ordering. They employ a genetic algorithm to solve the model. In [10] the authors propose a mixed integer programming model that considers material quantity discount and space availability. To the best of our knowledge, all the previous researches define an order plan to transport nonrenewable resources to the projects' worksites. Our study aims at extending modeling framework from defining a transportation plan to a production-transportation one by planning the supply chain network that produce and supplies the non-renewable resources. Beside of planning the processes related to forward supply chain, the proposed modeling framework also takes into consideration

backward processes to define a plan for transporting the produced wastes from the projects worksites to recycling units which are located, either in manufacturing centers, or in individual recycling centers.
It is worth mentioning that two main approaches are considered in network building of the resource constrained project scheduling models: 1- Single project approach, which joins the multiple projects together to provide a single super-project. In this approach a single critical path is regarded to schedule the activities of the projects. For the research works and different extensions we refer the reader to following references, [2], [4] and [11]. 2- Multi projects approach, wherein the parallel projects are targeted to schedule simultaneously. In this context, each of the projects maintains its own critical path, [12]. Therefore, it is more realistic for scheduling of multiple projects, [13]. In our study, we employ the second approach.
From the view point of complexity, scheduling the project(s) under the constrained resources belongs to NP-hard combinatorial optimization problems, [14]. According to [15], once projects become larger, that is more than 60 activities from PSPLIB of Kolisch and Sprecher presented in [16], the optimal methods become computationally intractable. To cope with the intractability, numerous heuristic and metaheuristic have been proposed in the literature. A comparison of the methods on a set of benchmarks is provided in [17] and [18].
Regarding the literature, the objectives in resource constrained project scheduling problems can be classified in five major groups: (i) Time-based objectives, in order to minimize targets such as completion time, earliness, tardiness and lateness [19]; (ii) Quality-based objectives, for maximizing the projects' quality [20]; (iii) Cost-based objectives in which the objective function presents minimization of the total cost of projects like as execution costs, material costs, inventory holding costs, costs related to tardiness or earliness of the project, [21]; (iv) Net present value, to maximize the present value of money in project scheduling. [22]; and, (v) multi objective models that consider simultaneously two or more of the conflicting objectives mentioned above, [23]. In this study, our objective is to minimize the total cost. Besides the costs related to running the projects, it encompasses as well the costs of nonrenewable resources' production and transportation, which are originated from operating the supply chain network.
Figure 1 depicts general schema of the modeling framework. It stands out three major unit types of the system's network (i. units in forward flows of the supply chain network, ii. projects' worksites and iii. units in backward flows of the supply chain) and presents main factors from a unit that affect the other unit(s).

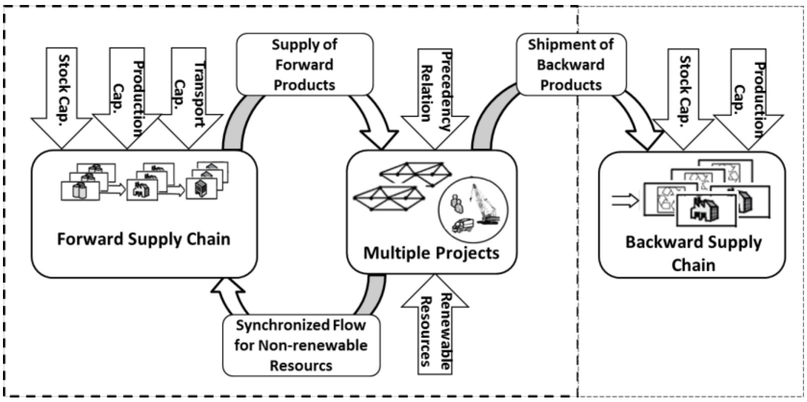

Figure 1: Presentation of interacting factors in supply chain and multiple projects.

2 Mathematical Model and Results

2.1 Formulation

Following notation is used to present the mathematical model:

Indexes:

i : index of activities.
t: index of time periods.
w: index of projects' worksites.

m : index of manufacturing centers.
c: index of recycling centers.
u: index to show all units of the network, including the worksites, *w*, manufacturing centers, *m*, collection-recycling centers, *c*, and *s* suppliers of raw materials.
nr: index of products used at the worksites (projects' non-renewable resources).
g: index of wastes types generated at the worksites.
p : index of network's product items, including of the products used at the worksites, *nr*, wastes generated at the worksites, *g*, composing elements/ raw materials used at the manufacturing centers and products produced at the manufacturing centers .
r: index of renewable resources used at the worksites.
r': index of high rent cost renewable resources used at the worksites, $r' \epsilon R$.
f(o,d,p) : index of flows which present the shipment of product *p* from origin *o* to destination *d*, $o \epsilon U$, $d \epsilon U$, $p \epsilon P$.
in(d,p): index of pairs which show reception of product *p* at destination *d*, $d \epsilon U$, $p \epsilon P$.
out(o,p) : index of pairs which show shipment of product *p* from origin *o*, $o \epsilon U\text{-}S$, $p \epsilon P$.
l: index of lines, including *lp* as production lines and *lc* as recycling lines.
pro(l,u,p) : index which identifies line type *l* at unit *u* which is dedicated to produce/recycle product *p*.
$\mathrm{b(p, p')}$: index to present linkage between composing element p and made product p'.

Sets:

Capital letters of following indices i, t, w, m, c, u, nr, g, p, r, r', s ,f(o,d,p), in(d,p), out(o,p), l, pro(l,u,p) and $b(p, p')$ are used to present related set notation.
I_w : set of activities that belong to worksite, ($I_w \subset I$).
SSpre : start to start precedence relation of activity *j* by pairs (*i, j*).
SFpre : start to finish precedence relation of activity *j* by pairs (*i, j*).
FSpre : finish to start precedence relation of activity *j* by pairs (*i, j*).
FFpre : finish to finish precedence relation of activity *j* by pairs (*i, j*).
$\mathrm{Nowait}_{\mathrm{SSpre}}$: 1 if activity *j* of precedence relation SSpre starts immediately after activity *i* has started, 0 otherwise.
$\mathrm{Nowait}_{\mathrm{SFpre}}$: 1 if activity *j* of precedence relation SFpre finishes immediately after activity *i* has started, 0 otherwise.
$\mathrm{Nowait}_{\mathrm{FSpre}}$: 1 if successor activity *j* of precedence relation *pre* starts immediately after finishing the predecessor activity *i*, 0 otherwise.
$\mathrm{Nowait}_{\mathrm{FFpre}}$: 1 if successor activity *j* of precedence relation *pre* finishes immediately after finishing the predecessor activity *i*, 0 otherwise.
φ_{w} : linkage (*i, j*) presents beginning activity of worksite w by *i* and ending one by *j*.
$\varphi'_{\mathrm{r'}\,\mathrm{w}}$: linkage (*i, j*) presents beginning activity of worksite w which uses renewable resource r' by *i* and the ending activity by *j*.

Parameters:

$\mathrm{e_i}$: earliest start of activity *i* .
$\mathrm{l_i}$: latest start of activity *i* .
$\mathrm{DD_i}$: due date of activity *i*.
$\mathrm{Du_i}$: duration of activity *i*.
$\mathrm{Dnr_{i,nr}}$: demand of activity *i* for nonrenewable resource *nr*.
$\mathrm{Dr_{ir}}$: demand of activity *i* for renewable resource *r*.
$\mathrm{FS_{ij}}$: minimum time lag between the finish of activity *i* and the start of activity *j*.
$\mathrm{SS_{ij}}$: minimum time lag between the start of activity *i* and the start of activity *j*.
$\mathrm{SF_{ij}}$: minimum time lag between the start of activity *i* and the finish of activity *j*.
FF_{ij} : minimum time lag between the finish of activity *i* and the finish of activity *j*.
$\mathrm{Ar_r}$: availability of renewable resource *r*.
$\mathrm{Max_r}$: maximum add value for resource r.

Pc_w : cost of running worksite w per period.
$Cc_{r'w}$: cost of using renewable resource r' at worksite w per period.
Rc_r : rent cost of renewable resource *r*.
$Penc_i$: penalty cost for one-period delay of filling up activity *i*.
$StinCap_u$: capacity for stocking the products which are using at unit *u*.
$StoutCap_u$: capacity for stocking the products which are produced at unit *u*.
$TnCap_u$: transportation capacity of unit u.
$StCof_p$: occupied space by product p.
$LAvCap_{lt}$: production capacity of line *l* at time period *t*.
$MaxAdd_l$: maximum add capacity in line *l*.
$AddCost_l$: cost for adding one unit of production/recycling capacity to line *l*.
Wl_p : workload of product *p*.
$Tc_{f(o,d,p)}$: cost for shipping one unit of product *p* from origin *o* to destination *d*.
$Tl_{f(o,d,p)}$: lead-time for shipping one unit of product *p* from origin *o* to destination *d*.
$Pl_{pro(l,m,p)}$: production time of product *p* at line *l* of manufacturing center *m*.
$StinC_p$: stocking cost for one unit of used product *p*.
$StoutC_p$: stocking cost for one unit of produced product *p*.
$StCof_p$: coefficient presents space occupied par one unit of a product p.
$ProdC_p$:production/recycling cost of product *p*.
$AddCL_l$:cost for adding one unit of capacity to line *l*.
$V_{b(p,p')}$: value of composing element in final product.
Gp_{gi} : waste type *g* generated by activity *i*.

Decision variables:

Z_{it}: 1 if activity *i* starts at time *t*, 0 otherwise.
U_{it}: 1 if activity *i* is processing over time t, 0 otherwise.
$Ltns_i$: lateness of activity *i*.
S_i: start date of activity *i*.
R_{rt} : Added quantity of renewable resource *r* over time period *t*.
$TQ_{f(o,d,p),t}$: transported quantity of product *p* from origin *o* to destination *d* at time *t*.
$Stin_{in(d,p),t}$: stock of product type *p* that is received at destination *d* at time ***t***.
$Stout_{out(o,p),t}$: stock of product type *p* that are sent from origin *o* at time ***t***.
$ProdQ_{pro(l,u,p),t}$: produced/recycled quantity of product *p* on line *l* of unit *u* at time *t*.
$AddL_{lt}$: quantity of added capacity to line *l* at time ***t***.

Objective function: Min Z =

$$\Big[\sum_w \sum_{(i,j)\epsilon\varphi_w} (S_j + Du_j - S_i)Pc_w + \sum_w \sum_{r'} \sum_{(i,j)\,\epsilon\,\varphi'_{r'w}} (S_j + Du_j - S_i)Cc_{r'w} + \sum_i Ltns_i\, Penc_i + \sum_r \sum_t R_{rt}\, Rc_r\Big] + \Big[\sum_{f(o,d,p)} \sum_t TQ_{f(o,d,p),t}\;\; TC_{f(o,d,p),t} + \sum_{in(d,p)} \sum_t Stin_{in(d,p),t}\;\; StinC_p + \sum_{out(o,p)} \sum_t Stout_{out(o,p),t}\;\; SoutC_p + \sum_{pro(l,u,p)} \sum_t ProdQ_{pro(l,u,p),t}\;\; ProdC_p + \sum_l \sum_t AddL_{lt}\;\; AddCL_l\Big] \quad (1)$$

The objective of the model is to minimize total cost of the system. It is made up of two types of cost: - *Project planning costs* (terms include in the first bracket), which are respectively total cost of running the projects, costs related to the renewable resources whose rent cost is high(The aim is to minimize the period that these resources are maintained at the worksites.), total penalty cost and total cost of adding supplementary renewable resources.- *Supply chain planning cost* (terms in the second bracket), including the total transportation cost for shipping products, stock cost of the products that are received at the destinations, stock cost of the products that are sent from an origin, production/recycling cost and the cost related to add of new production/recycling capacities in the related lines.

Subject to

$\sum_{t=e_i}^{l_i} Z_{it} = 1$ $\quad \forall i \in I$ (2)

$\sum U_{it} = Du_i$ $\quad \forall i \in I$ (3)

$S_j \geq S_i + Du_i + FS_{ij}$ $\quad \forall (i,j) \in FSpre, Nowait_{FSpre} = 0$ (4)

$S_j = S_i + Du_i + FS_{ij}$ $\quad \forall (i,j) \in FSpre, Nowait_{FSpre} = 1$ (5)

$S_j \geq S_i + SS_{ij}$ $\quad \forall (i,j) \in SSpre, Nowait_{SSpre} = 0$ (6)

$S_j = S_i + SS_{ij}$ $\quad \forall (i,j) \in SSpre, Nowait_{SSpre} = 1$ (7)

$S_j + Du_j \geq S_i + SF_{ij}$ $\quad \forall (i,j) \in SFpre, Nowait_{SFpre} = 0$ (8)

$S_j + Du_j = S_i + SF_{ij}$ $\quad \forall (i,j) \in SFpre, Nowait_{SFpre} = 1$ (9)

$S_j + Du_j \geq S_i + Du_i + FF_{ij}$ $\quad \forall (i,j) \in FFpre, Nowait_{FFpre} = 0$ (10)

$S_j + Du_j = S_i + Du_i + FF_{ij}$ $\quad \forall (i,j) \in FFpre, Nowait_{FFpre} = 1$ (11)

$\sum_{k=t}^{t-1+Du_i} U_{ik} \geq Du_i Z_{it}$ $\quad \forall i \in I, t \in \{e_i, \ldots, l_i\}$ (12)

$S_i = \sum_{t=e_i}^{l_i} t Z_{it}$ $\quad \forall i \in I$ (13)

$Ltns_i \geq S_i + Du_i - DD_i$ $\quad \forall i \in I$ (14)

$\sum_{i \in I} Dr_{ir} U_{it} \leq Ar_r + R_{rt}$ $\quad \forall r \in R, \forall t \in T$ (15)

$R_{rt} \leq MAXR_r$ $\quad \forall r \in R, \forall t \in T$ (16)

$Stin_{in(m,p),\ t-1} + \sum_f TQ_{f(o,d,p|\ d,p \in In(m,p)),\ t-Tl_{f(o,d,p|d,p \in In(m,p))}} =$
$Stin_{in(m,p),\ t} + \sum_{b(p,p')|\ p \in In(m,p)} \sum_{pro} ProdQ_{pro(lp,m,p')|\ p' \in b(p,p'),t}\ V_{b(p,p')}$
$\forall in(d,p) \in IN(m,p), t \in T$ (17)

$Stin_{in(d,g),t-1} + \sum_f TQ_{f(o,d,p|\ d,p \in In(d,g)),t-Tl_{f(o,d,p|d,p \in In(d,g))}} =$
$Stin_{in(d,g),\ t} + \sum_{pro} ProdQ_{pro(lc,u,p)|u,p \in In(d,g),\ t}$ $\quad \forall in(d,p) \in IN(d,g), t \in T$ (18)

$Stin_{in(w,nr),t-1} + \sum_f TQ_{f(o,d,p|d,p \in In(w,nr)),\ t-Tl_{f(o,d,p|d,p \in In(w,nr))}} =$
$\sum_{i \in I_w} Z_{it} Dnr_{i,nr|nr \in In(w,nr)} + Stin_{in(w,nr),\ t}$ $\quad \forall in(d,p) \in IN(w, nr), t \in T$ (19)

$Stout_{out(m,p),\ t-1} + \sum_{pro} ProdQ_{pro(lp,u,p|u,p \in OUT(m,p)),\ t-Pl_{pro(lp,u,p|u,p \in OUT(m,p))}} =$
$\sum_f TQ_{f(o,d,p|o,p \in OUT(m,p)),t} + Stout_{out(m,p),\ t}$ $\quad \forall out(o,p) \in OUT(m,p), t \in T$ (20)

$Stout_{out(w,p),\ t-1} + \sum_{i \in I_w} Z_{it} Gp_{g|g \in OUT(w,p),\ i} = \sum_f TQ_{f(o,d,p|o,p \in OUT(w,p)),\ t} + Stout_{out(w,p),\ t}$
$\forall out(o,p) \in OUT(w,p), p \in G, t \in T$ (21)

$ProdQ_{pro(l,m,p),t}\ Wl_p \leq LAvCap_{lt} + AddL_{lt}$ $\quad \forall pro(l,u,p) \in PRO(l,m,p), t \in T$ (22)

$AddL_{lt} \leq MaxAdd_l$ $\quad \forall l \in L, t \in T$ (23)

$\sum_p Stin_{in(d,p)|d \in u,t}\ \mathrm{StCof_p} \leq StinCap_u$ $\quad \forall u \in U, t \in T$ (24)

$\sum_p Stout_{out(o,p)|o \in u,t}\ \mathrm{StCof_p} \leq StoutCap_u$ $\quad \forall u \in U, t \in T$ (25)

$TQ_{f(o,d,p)|o \in u,t} \leq TnCap_u$ $\quad \forall u \in U, f(o,d,p) \in F(u,d,p), t \in T$ (26)

$Stin_{in(d,p),t} = 0$ $\quad \forall in(d,p) \in IN(d,p), t=0,T$ (27)

$Stout_{out(o,p),t} = 0$ $\quad \forall out(o,p) \in OUT(o,p), t=0,T$ (28)

$Z_{it}, U_{it} \in \{0,1\}$ $\quad \forall i \in I, t \in T$ (29)

$Ltns_i, S_i, R_{rt}, TQ_{f(o,d,p),t}, Stin_{in(d,p),t}, Stout_{out(o,p),t},$
$ProdQ_{pro(l,u,p),t}, AddL_{lt} \geq 0$
$\forall f(o,d,p) \in F(o,d,p), in(d,p) \in In(d,p), out(o,p) \in OUT(o,p), pro(l,u,p) \in PRO(l,u,p), l \in L, i \in I, r \in R, t \in T$ (30)

Considering earliest, latest start time and precedence relationships, constraints (2)-(13) define start time of the activities. Constraint (14) takes into account lateness may happen in completion of the activities. Constraint (15) guarantees that all demand of activities for renewable resources is satisfied by the initial available quantity and quantity could be added. Constraint (16) defines a maximum value for adding the nonrenewable resources. Equations (17), (18) and (19) present balance constraints of the supply chain for products that are used in a destination. Constraints (20) and (21) present the same concept for the products that are sent from an origin. Constraint (22) impose that the production/recycling of the products cannot exceed the available capacities plus the capacities could be added. Constraint (23) defines a limit for added capacities. Constraints (24) and (25) deal respectively with the stock capacity related to the products that are used in a destination and the products which are sent from an origin. Constraint (26) imposes transportation capacities. Equations (27) and (28) take into consideration initial and final states of the stocked products.

2.2 Use Case and Results

The results are obtained by use of CPLEX-Studio 12.6.1 on a case hails from CRIBA (Construction Industrialisée Bois et Acier) project. The project is defined to increase energy efficiency of buildings in France. For that purpose insulating panels are supposed to be installed on external facade of the buildings to cover the buildings and reduce their energy consumption level. Main composing elements of the panels are wooden frames, insulation material types, insulating carpentries and external coating materials. Each element is supplied by its corresponding suppliers/manufacturers. Several renewable resources such as labor-works, trucks and cranes should be present at the worksites to make progress on installing the panels. In this context, some kind of renewable resources such as the cranes hold high rent cost. Therefore, the aim is to reduce the time interval that these resources should be maintained in the projects' worksites. After installation of the panels, former carpentries of the buildings should be removed. In order to respect the sustainability engagements, the produced wastes are supposed to be shipped to proper recycling centers. Dimension of the case and the obtained results are depicted in Fig. 2, Fig. 3 and Fig. 4.

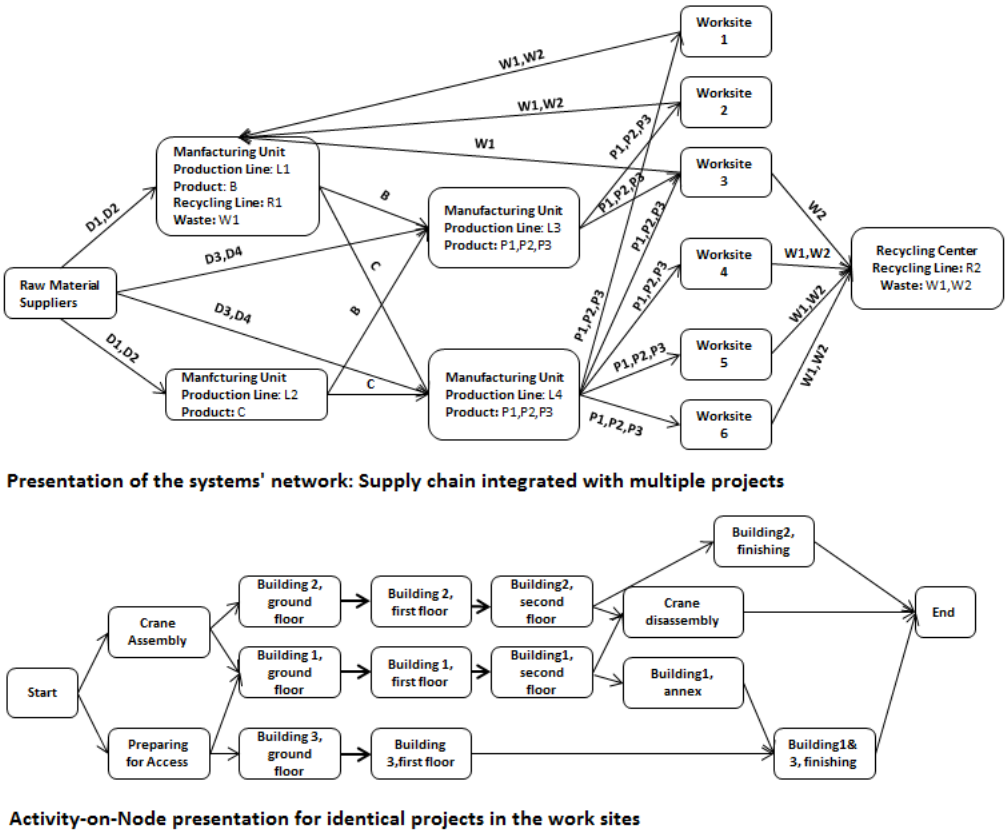

Figure 2: Presentation of the system framework dedicated for use case.

Regarding the results in Fig.3 we could point out although all of the projects have the same data setting, staring date for source/sink activities of the projects are not the same. This challenge originates from (i) the supply of the nonrenewable resources and (ii) from the strategy for assigning the renewable resources to the activities to make them able to be started on a time between their earliest start and latest start time. From the view point of (i), the supply chain ships the final products to the worksites regarding (a) its limited capacity of supply and (b) the flexibility that projects activities provide via their possible time windows of execution (earliest start time and latest start time). Based on (a) and (b), different start times can be associated to execution of the projects' activities. From the view point of (ii), the model defines the start dates for the activities based on the availability of the renewable resources, probable rented resources and also flexibility that activities have for effectuation (earliest start and latest start). In this context, regarding the due date of activities, the model makes decision, either to start an activity by renting additional quantity of low cost renewable resources and avoid paying high penalty cost, or make delay with the aim of paying low cost penalty cost and not to pay for high rent cost of renewable resources. Fig. 4 presents the results obtained from sensitivity analysis. As it is depicted in the figure, by decrease in the add cost of resources, there is no considerable change on total penalty cost. Nevertheless by increase in the renewable resources' add cost, from the point of 40% of increase, the model moderates the total add cost of the resources by accepting to pay penalty cost in order to not pay high cost of adding the resources.

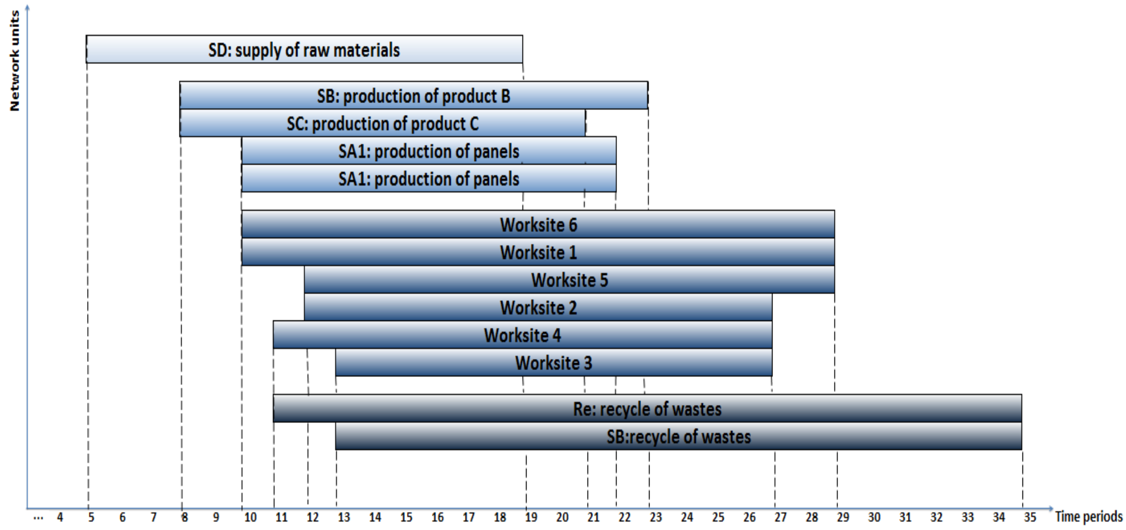

Figure 3: Presentation of working periods of the network units.

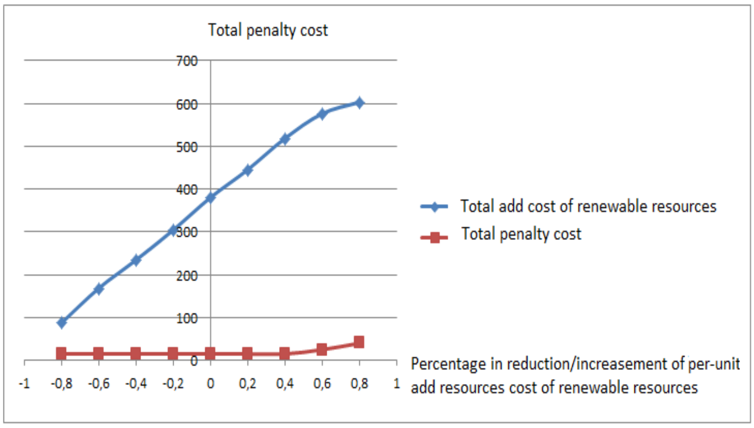

Figure 4: Sensitivity analysis presentation for variation in per-unit rent cost of renewable resources.

3 Conclusion and Future Work

This study presents a GRCMPSP with two types of nonrenewable and renewable resources. In order to define a production-transportation plan to feed up the non-renewable resources, it integrates a multi-project planning model with a typical supply chain planning model. Furthermore, to provide an assignment plan for the renewable resources, it assumes possibility of adding supplementary quantities in initial availability of the renewable resources over the periods in which the requirement for the resources may exceed the initial quantity. Taking into consideration due-dates of activities leads the model to decide, either to rent additional capacities of renewable resources and not to pay as much as it is possible, or to pay for low penalty cost instead of paying for high rent cost renewable resources. For future works, the authors are interested in applying a proper metaheuristic algorithm to deal with large sizes problems. It also draws attention to reduce total number of binary variables Z_{it} ,$\sum_f (l_i - e_i)$, by a heuristics which limits l_i and e_i to make tighten $[e_i - l_i]$.

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