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RESEARCH ARTICLE

Coordinated Planning and Scheduling of Multiple Projects With New Projects Arrival Under Resource Constraint Using Drum Buffer Rope Heuristic

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ABSTRACT Planning and scheduling of multiple projects is significant for efficient utilization of constraint resources. However, in most of the project based companies, planning and scheduling of projects is performed in hierarchical manner with less focus given on coordination between the planning and scheduling levels, which leads to make inefficient plans and cause delays in projects and underutilize the resources. Therefore, current research is focused on coordinated planning and scheduling of multiple projects under resource constraints. Further, arrival of new projects in the planning horizons is also considered during planning and scheduling of multiple projects in planning horizons. Current research proposed drum buffer rope heuristic (DBRH) for coordinated planning and scheduling of multi projects with new projects arrival in rolling horizon. The proposed DBRH integrates higher level planning (HLP) with medium level planning (MLP), identify the critical activities of multiple projects, determine the capacity constraint sharing resources (CCSR) and make efficient plan and schedule of multiple projects with an aim to minimize the total tardiness of multiple projects. Moreover, in each planning horizon, the multiple project activities are updated using push and pull strategies in DBRH to maximize the utilization of CCSR. The performance of the DBRH is measured with the performance of standard genetic algorithm (GA), simulated annealing (SA), GA with priority of maximum tardiness project (GA-MTP) and SA with priority of maximum tardiness project (SA-MTP) based on simple project data, standard benchmark project data and Case Company data. Experimental results indicate that the proposed DBRH gives better results as compared to the other heuristics including GA, SA, GA-MTP and SA-MTP.

INDEX TERMS Heuristic, drum buffer rope, capacity constraint resource, project scheduling, multi-level planning.

I. INTRODUCTION

A. RESOURCE CONSTRAINT MULTIPLE PROJECT SCHEDULING PROBLEM

Resource constraint project scheduling (RCPSP) is an extension of the classical project scheduling problem in which an additional constraint of the resource capacity is considered along with precedence constraints of the project activity [1]. RCPSP is a combinatorial problem used to schedule set of precedence activities of projects on limited resources [2]. For detailed introduction to RCPSP, see literature reviews on project scheduling problem [3]–[5]. The RCPSP problem has been extensively researched in literature. However, according to studies, 80% to 90 % of all projects in worldwide are executed in multi-project environment [6], [7] and single project scheduling problem are rarely used in industries [8].

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Therefore, current research is focused on resource constraint multi project planning and scheduling problem.

Multi-project scheduling is significant for project based industries which are running multiple number of projects in parallel with limited resources. Resource constraint multi-project scheduling problem (RCMPSP) is an extension of classical RCPSP which involves simultaneous consideration of the precedence constraints of two or more projects with sharing resources of limited capacities [9]. In RCMPSP in addition to the precedence constraints of individual projects and the limited capacities of resources, waiting times on the start time of the activities of multiple projects are also involved due to limited capacities of the sharing resources. Companies have challenge to manage multiple projects keeping in view of all the precedence constraints including precedence constraint of activities of each individual project and starting time constraints of the activities of multi-projects considering sharing resources.

In literature, multi-project scheduling problem has been addressed by researchers in static and in dynamic environment. The RSMPS problem in static environment assumes closed portfolio of multi-projects where once multiple number of projects are scheduled, no rescheduling is performed in it. Whereas, RCMPSP in dynamic environment of multi-projects considers an open portfolio of projects where projects are arriving in the dynamic pattern in different planning horizons. RCMPSP in static environment has been extensively researched [8], [10]–[15]. However, most of the project based industries are running multi-projects in dynamic environment where already planned projects are executed and at the same time new projects are arriving. Therefore, multi project scheduling problem in dynamic environment has been investigated in literature by several researchers. For example, Yang and Sum [16], [17] studied multi project scheduling in dynamic environment and presented a two level scheduling method. In the higher level, resources are assigned to the activities of the projects and in the lower level, the activities on resources are scheduled in their proposed method. Ash and Smith-Daniel [18] focused on the learning, forgetting and relearning cycle in dynamic multi-project environment. Anavi-Isakow and Golany [18] applied queuing theory and used production management concepts to multi-project environment. Artigues *et al.*, [19] proposed a new polynomial insertion algorithm for dynamic resource constraint multi-project scheduling problem. Krüger and Scholl [8] considered a RCMPSP with the addition of transfer time of the resources. They proposed a generalized multi-project scheduling problem including sequence and resource-dependent transfer times. Araúzo *et al.*, [20] proposed a dynamic scheduling approach for multi-project scheduling using simulation method. Wang *et al.*, [21] proposed a multi-objective optimization model for multi-project scheduling on critical chain, which takes into consideration multi-objectives, such as overall duration, financing costs and whole robustness. Pamay *et al.*, [22] proposed a conceptual framework for dynamic resource constraint multi project scheduling problem with weighted earliness and tardiness cost. Zheng *et al.*, [23] proposed a critical chain based approach for multi-project scheduling. Yassine *et al.*, [24] studied scheduling of resource constraint multi-projects in dynamic environment and proposed a genetic algorithm to solve their considered problem. Melchiors *et al.*, [25] integrated the order acceptance and capacity planning of multi-projects in dynamic environment and considered capacity of bottleneck resource. They considered dynamic arrival of projects and accept or reject the projects utilizing macro process planning and Marcov decision process. Recently, Hao Jie Chen *et al.*, [26] investigated resource constraint multi-project scheduling problem and considered arrival of new projects in the project portfolio for the first time in literature. They proposed priority rules for scheduling of RCMPSP including new projects. RCMPSP considering dynamic environment of projects is significant to manage multi projects in dynamic environment.

Nonetheless, most of the literature on multi project scheduling problem has focused on single level of planning involving scheduling of activities of the projects and have not considered coordinated planning and scheduling together. Planning of multi projects can set the targets and scheduling of multi project activities is used to make efficient schedule according to the plan and they are interdependent on each other and their efficiency can be improved to get global optimal solution if the planning and scheduling are integrated. Planning of multi projects at higher level for long term planning horizon and scheduling of multi project activities at medium level of planning horizons need to be consider together for multi projects and is therefore considered in the current research.

B. ROLLING HORIZON PLANNING

In most of the companies, the planning is considered in a rolling horizon pattern [27]–[29]. Rolling horizon planning is significant for industries to update the plan after each planning horizon. Therefore, rolling horizon planning concept has been applied for planning problems in supply chain [30], [31], lot sizing and scheduling [32]–[34] material requirement scheduling [35], forecasting [36]–[39] inventory planning [40] master production scheduling [41] and multi-level planning of mixed model production system [42]. Sahin *et al.*, [43] highlighted literature studies on rolling horizon planning. Rolling horizon planning has been studied for rolling horizon planning in supply chain [30]; Maxime Ogier *et al.*, [31]. In addition, rolling horizon planning has also been investigated to optimize the parameters of planning horizons [35]–[41], [44] and optimization of lot sizing and scheduling decisions [32]–[35], [45]. Krajewski and Wei [46] studied integration of schedule in rolling horizon in stochastic environment in supply chains and investigated master production schedule design factors. Mazime Ogier *et al.*, [31] studied rolling horizon planning in supply chain. In addition, Barrett and Laforge [35] investigated the planning frequency on the performance of production system on multiple levels in material requirement planning (MRP). Zhao and Lee [36] studied the impact of forecast errors in rolling horizon planning. Ho and Ireland [37] and Venkataraman and D'Itri [38] studied impact of forecast error on planning instability. Boulaksil *et al.*, [40] studied rolling horizon planning in supply chain. Thomas Ponsignon and Lars Monch, [41] investigated master production planning (MPS) for a semiconductor manufacturing industry in rolling horizon. Idris Lalami *et al.*, [42] studied rolling horizon planning in automobile powertrain plant. Timm Ziarnetkzy *et al.*, [39] studied a production planning model for semiconductor wafer manufacturing facility in rolling horizon. Clark and Clark [33] studied parallel machine lot sizing and scheduling problem in rolling horizon. Stadtler [45] investigated multi-level lot sizing problem in rolling horizon. Araujo *et al.*, [32] modified general lot sizing and scheduling problem in rolling horizon pattern. Tiacci and Saetta [34] studied lot sizing and scheduling problem in rolling horizon. Recently, Saif *et al.*, [42] studied rolling horizon planning for mixed model production environment. However, rolling horizon planning concept has not been applied for RCMPSP in dynamic environment. In addition, a literature review presented by Sahin *et al.*, [33] also showed that there no research work found on rolling horizon planning of RCMPSP in literature. Resource constraint multi-project planning in rolling horizon is significant for project based companies to plan multi-projects in dynamic environment.

In literature, two strategies have been used for resource constraint multi project scheduling problem, including independent solution [31] and combined solution combined solution [10]. In the independent solution approach, each individual project has its own start node and end node. This method my not be significantly used to manage dynamic arrival of new projects in the portfolio since each project in the portfolio is treated individually and may not efficiently considers dynamic arrival of projects. In the combined solution method, the precedence constraint of the multi projects are combined to make a combined project containing precedence constraints of all projects with only one start node and one termination node. In the combined solution method, the precedence constraints of all projects are considered to make a single project. This method can consider the critical chain of the combined project for planning and scheduling of activities of all projects. The critical chain of the combined project may contain different activities as critical and these activities could be from different projects. Therefore, in the dynamic environment of multi projects in the portfolio, the combined project needs to update its activities in rolling horizon when new projects are inserted in portfolio in dynamic environment in planning horizons. In literature, only Hao Jie Chen *et al.*, [26] have considered insertion of new projects for resource constraint scheduling of multi-projects and proposed priority rules of scheduling. The insertion of new projects in the portfolio in planning horizons needs modification in the combined project considering precedence constraints of the existing projects and the new project in the portfolio in rolling horizon pattern. However, there is no work found in literature considering RCMPSP with insertion of new projects in the portfolio and dynamic update in the combined project of multi-projects in rolling horizon pattern and it is considered for the first time in the current research.

C. DRUM BUFFER ROPE METHOD

Drum buffer rope (DBR) method is a direct application of theory of constraint in which the drum is considered as a capacity constraint resource (CCR). DBR method is used to improve the production based on the improvement on CCR. BDR has been defined for production planning and control. For example, DBR based production planning and control mechanism for make to stock (MTS) environment [47] and make to order (MTO) environment [48] has been proposed in literature. In addition, DBR method has also been used for production planning and control in flowshop [49]; packaging problem of material [50], assembly shops [51] and scheduling of aircrafts [52] etc.

However, no research work found which has considered DBR concepts for multi project planning and scheduling problem. In multi project planning and scheduling problem, combined project activity diagram of multi-projects contains activities of all multi projects which may require different capacities of different resources. Some of the resources are shared among the activities of multi-projects and some of these shared resources are processing critical activities of the multi projects. The resource which limits the capacity in the considered planning horizon is considered here as capacity constraint resource (CCR). The capacity constraint resources which are being shared among the projects and needs processing of critical activities of multi-project are termed here as capacity constraint shared resources (CCSR). Where multi-projects are considered together for processing on resources, there is possibility of the addition of waiting times of the project activities in different schedules of multi-project activities on the shared resources. These waiting times of project activities are changed with the changing of their schedule on the shared resources. Therefore, the length of critical chain of multi-projects is not fixed when multi-projects are using limited resources and also sharing some resources in different planning horizons. There is possibility of changing of critical chain length of multi-projects and shifting of the capacity constraint sharing resources (CCSR) in each planning horizon in dynamic environment of multi-projects. In the current research, a rolling horizon planning and scheduling of multi projects considering shifting of CCSR in each planning horizon is considered along with arrival of new projects in the portfolio. Since, in most of the real manufacturing systems, there is dynamic changes in the demand of project and orders [50] therefore, current research uses a feedback information of the optimal schedule on CCSR resource in each medium level planning horizon ahead of it and updates the medium level and higher level plan in rolling horizon. This method is significant to maximize the utilization of CCSR resources in each medium level planning horizon in rolling horizon and also provides time buffer to prepare material in each medium level planning horizon.

Resource constraint project scheduling problem is NP-hard problem [9]. It has been researched in literature with different solution methods to get its near optimal solutions in reasonable computation [9], [16], [17]. Fendley [53] presented multi-project scheduling problem and proposed priority rules. Kurtulus and Narula [54] introduced priority rules for multi-project scheduling. Dumond and Mabert [55] presented different heuristics and strategies to assign due dates to the projects. In their research, flow time of projects, critical chain of projects and scheduled finished time of projects have been analyzed. Tsubakitani and Deckro [56] developed a heuristic method for multi-project scheduling with resource constraints. Khattab M, Choobineh [57] introduced a new heuristic for project scheduling with single resource constraint. Shankar and Nagi [58] used simulated annealing method for multi-project planning problem. Lova and Tormos [7] used heuristic rules for resource constraint multi-project scheduling problem. Hartmann [59] proposed a self-adaptive genetic algorithm for project scheduling considering resource constraints. Kolisch, R. and S. Hartmann [5] studied resource constraint project scheduling problem and proposed a heuristic solution. Gonçalves *et al.*, [10] developed a genetic algorithm to solve multi-project scheduling problem. Krüger, D., Scholl, A [8] investigated a multi-project scheduling problem and proposed a heuristic method to schedule the activities of multi-projects in static environment. Mendes *et al.*, [60] proposed a random key-based genetic algorithm for resource constraint project scheduling problem. Browning T R, Yassine [11] presented heuristic rules for resource constraint multi-project scheduling problem. Asta *et al.*, [12] used Monte carlo method and a heuristic method for resource constraint multi-project scheduling problem. Wang Y, *et al.*, [13] studied the performance of priority rules for resource constraint multi-project scheduling problem. Kadri *et al.*, [61] proposed an efficient genetic algorithm to solve the resource-constrained project scheduling problem. Hao Jie Chen *et al.*, [26] investigated resource constraint multi-project scheduling problem considering arrival of new projects in the project portfolio and proposed priority rules for scheduling of RCMPSP. Naihui He *et al.*, [62] proposed a multiagent approach for integrated multi project planning and scheduling. Zsolt T. Kosztyán [63] proposed an exact algorithm for flexible mltiproject scheduling.

Nonetheless, most of the literature proposed heuristic methods to schedule projects at single level of planning. They mostly studied multi project scheduling to get optimal results and complete project activities in time. However, the scheduling of project activities can give effective results if the project plan is feasible and used to make optimal schedule. In most of the project based companies, the higher level plan (HLP) is made in higher level planning horizons to give the targets to the medium level planning horizons to make medium level plans (MLP). HLP is based on rough capacity estimates of resources and it is forwarded to the medium level planning horizons to be followed. However, the HLP is mostly made based on fixed capacity constraint resource CCR resource with its known capacity. Furthermore, in the dynamic environment of project based companies, the projects arrives dynamically in each planning horizon and the workload content of different activities of the projects are different on resources which causes shifting of the critical activities and causes shifting of capacity constraint shared resource (CCSR) in each MLP horizon. Therefore, HLP which is made and based on the known capacity of a fixed CCR resource may cause infeasible plan when it is executed and when the CCSR resource is shifting in MLP horizon. In addition, when multi-project activities are running on different CCSR, some of the activities of different projects can share these resources and some activities of the projects are critically affecting the overall completion time of the multi-projects. Critical chain is a set of activities of project which can determine the overall project duration taking into consideration of the precedence relation of the activities and resource dependencies [64]. The critical activities of multi-projects can define the overall completion time of the projects and scheduling of these activities can reduce the time to obtain optimal schedule of activities. It is the direct application of theory of constraint on project planning and it can improve the robustness of the project schedule. In literature, critical chain concepts for multi-project planning has been used by some researchers [21], [23], [64], [65]. However, most of the research have utilized it for either planning or scheduling of multi projects and have not considered it for planning and scheduling of multi projects in dynamic environment. In multi project environment, dynamically arriving multi-projects in higher level and medium level of planning horizons can change the workload content on different resources in each medium level planning horizon. Therefore, there is possibility that the set of critical activities may also change in each medium level planning horizon and at the same time the CCSR resources not remain fixed and can shift. The shifting of CCSR resource in each medium level planning horizon can change the set of critical activities of multi-projects and it may require change in the schedule of activities on CCSR resources. For dynamic environment of multi-project planning based on critical chain concepts, there is need to consider scheduling of critical activities on CCSR resource in each medium level planning horizon to get efficient project plan. Moreover, it is highly needed to do planning and scheduling of multi-projects together considering shifting of CCSR resource in each MLP horizon for multiple projects planning in dynamic environment and therefore, first time introduced in the current research.

Current research has following contributions:

- Current research is novel to present coordinated planning and scheduling of multi project under resource constraint.

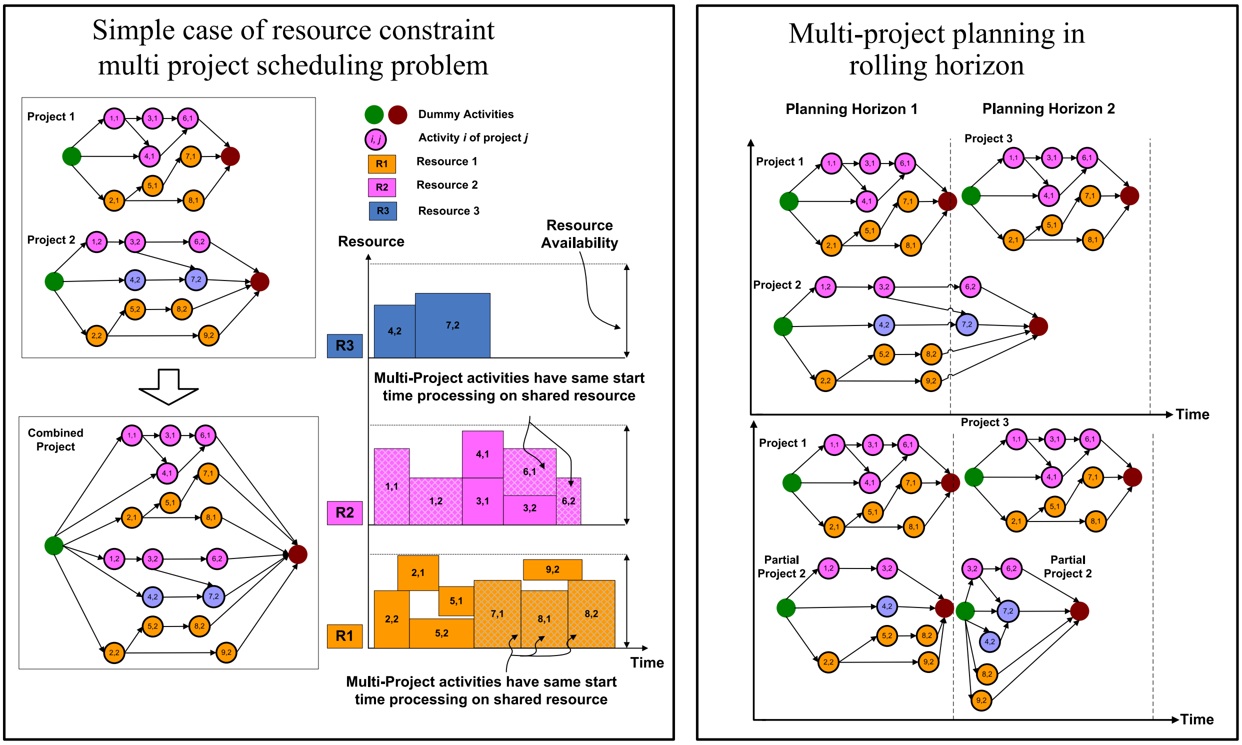


FIGURE 1. **Simple case of resource constraint multi project scheduling problem and multi-project planning in rolling horizon.**

- Current research is novel to introduce rolling horizon planning for of multi-projects to manage arrival of new projects in the portfolio in planning horizons.
- Current research introduced a novel drum buffer rope heuristic (DBRH) for planning and scheduling of multi-projects.
- Current research in novel to integrate HLP and MLP planning levels for multi projects

The managerial importance of the current research in industries lies to improve the usage of CCSR resource and equipment utilization in each planning horizon. In addition, the schedule prepared by the decision maker from DBRH can improve the completion of projects in due dates, improves the utilization of CCSR resources in each planning horizon, reduce the gap between the HLP and MLP and the plan made by DBRH are feasible when they are scheduled and implemented in the medium level planning horizons in each planning horizon.

II. PROBLEM DESCRIPTION

In project based companies, multiple projects are planned in parallel in each planning horizon with limited resources. Figure. 1 illustrates simple case of resource constraint multi project scheduling problem and multi-project planning in rolling horizon. It can be seen from Figure. 1 that in the simple case of resource constraint multi project scheduling of two projects is shown where Project 1 and Project 2 are executed simultaneously on three resources, Resource 1, Resource 2 and Resource 3 of fixed capacities. The two projects, Project 1 and Project 2 are combined together to make a combined project which stores the original precedence constraints of the activities of Project 1 and Project 2 in it. In multi project scheduling problem, there is possibility that two or more activities of the same or different projects may need the same resource at the same time. For example, activity 1 of project 1 and activity 1 of Project 2 are starting at the same time on resource 2. However, resource 2 can start one activity at a time due to its resource limitations, therefore, one of the activity, i.e., either activity 1 of project 1 or activity 1 of project 2 need to wait on resource 2. The other activities of the Project 1 and Project 2 which are sharing the resources and also need to process on the same resource at the same time are indicated in Figure 1. Resource constraint multi project scheduling problem is aimed to find the sequence of multi project activities on the resources keeping in view of the capacities of resource, precedence constraints of the activities.

The project activities of the combined project which are not completed in the current planning horizon are performed in the next planning horizon along with the projects received for the next planning horizon. It can be seen from Figure. 1 that the pattern in which a company can receive multi-projects from customers and their combined project is planned in rolling horizon. The project activities of the combined project which are not completed in the current planning horizon are partially completed in the current planning horizon and the remaining part of the project activities are considered as partial project and moved to process in the next planning horizon.

It can be seen from Figure. 1 that Project 1 is completed in the planning horizon while Project 2 is partially completed in the given time of planning horizon 1 and the project activities of Project 2 are partially completed in planning horizon 1 while partial project 2 is moved to the planning horizon 2. It can be seen from Figure. 1 that each planning horizon involves the plan of the new projects and the previously uncompleted activities of the projects from the previous planning horizons. This dynamically changing pattern of plan of different projects in each planning horizon is in the interests of the companies, if optimized. Further, it can be seen from Figure. 1 that the critical chain of combined project of multi-projects contains different sharing resources and in each sharing resource, schedule of different project activities can influence on the length of critical chain of combined project of multi-projects. For example, there is possibility of addition of waiting times to the starting time of activities on the sharing resources when two or more activities of same or different projects need the same resource at the same time. Scheduling of these activities can influence on the length of critical chain length of combined project of multi-projects while scheduling them on limited resources. This can increase the complexity in multi-project scheduling problem as the length of critical chain is changing as the schedule of activities on sharing resources is changed. Current research introduced the term of capacity constraint sharing resources (CCSR) as the capacity constraint resources (CCR) which are shared among the activities of multi-projects and they can influence on the critical chain length of the multi-projects.

Consideration of new projects arrival in the portfolio is significant and more realistic for dynamic scheduling of multi projects. However, insertion of new projects in the portfolio considering the duration of planning horizons and capacity of the bottleneck resources is important for dynamic scheduling of multi-projects. In addition, higher level planning of multi-projects for long term using a single or fixed bottleneck resource may not efficiently optimize the critical activities of the multi-projects.

Current research considers planning of multi projects in the HLP horizons by making combined project of multi projects activities in the HLP horizon by looking on the capacities of the CCSR which are performing critical activities of the combined project in the HLP. Further, current research makes an optimal schedule of project activities to maximize the utilization of CCRS and identifies the project activities which can be considered for planning in the next planning horizon to make their partial project. The detail of current research problem and its formulation is described in this section.

NOTATIONS

P	Set of projects
$P = 1, 2, \ldots, p, q, \ldots, N$	
$P_\tau \in P$	Set of projects containing activities in medium level planning (MLP) horizon τ, $0 < \tau \leq \Gamma$
T	High level planning (HLP) planning horizon
CPL_{pT}	Critical path length of project p in HLP horizon T
SB_{pT}	Shipping buffer time SB_{pT} of project p in HLP horizon T
$D_{(n_p+1)T}$	Due date of the project p in HLP horizon T
LS_{0pT}	Latest possible start time of p in HLP horizon T
ES_{0pT}	Earliest possible start time of p in HLP horizon T
PST_{pT}	Planned start time of p in HLP horizon T
$G_{p\tau} = \left(V_{p\tau}, A_{p\tau}\right)$	Activity on node network diagram of a project p in MLP horizon τ

A. ACTIVITIES

$V_{p\tau} = \{0, 1, \ldots, n_{p\tau}, n_{p\tau} + 1\}$	All activities and set of arcs of project p in MLP horizon τ

B. PRECEDENCE CONSTRAINTS OF PROJECTS

$A_{p\tau} = \{i_{p\tau}, j_{p\tau} \mid i_{p\tau}, j_{p\tau} \in V; i_{p\tau} \rightarrow j_{p\tau}\}$	Precedence constraints of project p in MLP horizon τ
$i_{p\tau} = 1, 2, \ldots., n_{p\tau}$	Activities from a project p which can start in MLP horizon τ
$i^c_{pk\tau} = 1, 2, \ldots., n^c_{pk\tau}$	Activities of the combined project belonging from a project p which can start in MLP horizon τ and process on resource k including the project activities which are partially completed in previous planning horizons.
$i^\partial_{pk\tau} = 1, 2, \ldots., n^\partial_{pk\tau}$	Activities from a project p which are partially completed in MLP horizon τ
$t_{ipk\tau}$	Processing time of an activity i_p of p which can start in MLP horizon τ and process on resource k
$T_{iP(X_k)k\tau}$	Processing time of activity i_p of project p which is processed at position X_k in the activity schedule on resource k in MLP horizon τ
$I^c_{pk\tau}$	Set of activities which have to start in the MLP horizon τ and it also includes the partially completed activities or the partial projects from the

	previous MLP horizons $0 < x \leq \tau - 1$
$i_{p\tau} \rightarrow j_{p\tau}$	Precedence constraints between the activities of the projects for all projects in HLP horizon τ, i.e., activity $j_{p\tau}$ cannot start before activity $i_{p\tau}$ is completed.
$S_{0p\tau}$ and $D_{(n+1)p\tau}$	Represent the starting time and finishing time of project p which is in MLP horizon τ
$S_{ip(X_k)k\tau}$	Start time of an activity i_p of a project p which can start processing at position X_k in the sequence of activities on a sharing resource k in MLP horizon τ
$R_{k\tau}$	Set of resources in MLP horizon τ
$R_{k(sh)\tau}$	Set of sharing resources in MLP horizon τ
$r^{p}_{ik\tau}$	A constant amount of resource k which is occupied due to activity i_p in a project p in MLP horizon τ
$\pi^{(ip)}_{R_k\tau}$	Sequence of activities $i_p = 1, 2, \ldots, n_p$ of project p on resource k in MLP horizon τ
$C_{ip(X_k)k\tau}$	Completion time of activity i_p of project p which is processed at position X_k in the activity schedule on resource k in MLP horizon τ
$C_{ip\tau}$	Completion time of activity i of project p in MLP horizon τ
$C_{n_pp\tau}$	Completion time of p in MLP horizon τ
$D_{(n_p+1)}$	Due date of the project p
AT_τ	Available time in MLP planning horizon τ
$Tardiness_p$	Tardiness of project p
CTP_τ	Set of critical tardy projects in MLP horizon τ
CFA_τ	Set of activities containing critical final activities of projects $p \in CTP_\tau$
TA_τ	Set of target activities which are considered to exchange in the schedule in MLP horizon τ
TAN	Represents the set of transitions which are allowed and they are not forbidden
$\pi^{(ip)}_{R_k\tau}(o)$	The multi project schedule with the minimum value of total tardiness obtained so far.
$\pi^{(ip)^z}_{R_k\tau}$	The Schedule generated by the z search iteration.
$TTardiness_{p\tau\pi(t)}$	Indicates the total tardiness of the multi project schedule that resulted from the transition t

$$TTardiness_{p\tau\pi} = \sum_{p=1}^{N} Tardiness_{p\tau}$$

$$Tardiness_{p\tau} = \max\left\{0, C_{n_pp\tau} - D_{(n_p+1)}\right\}$$

$TT_{p\tau\pi}$	Indicates the total tardiness of the multi project schedule $\pi^{(ip)}_{R_k\tau}$

RCPSP of a single project is explained in this section. The objective of resource constraint project scheduling problem is to minimize the tardiness of the project p, as indicated in Equation (1). The constraints of the problem are indicated in Equation (2) to Equation (6). Equation (2) shows the completion time of an activity i of project p in MLP horizon τ. Equation (3) shows that the starting time of the project is earlier than the start time of activities of the project. The sum of resource requirement of the activities of project should not exceed the total amount of resource available, as indicated in Equation (4). The tardiness of activities is represented in Equation (5). The completion time constraint of project activity is shown in Equation (6).

$$Obj = \min\left(Tardiness_p\right), \quad \forall p \tag{1}$$

$$C_{ip\tau} \geq S_{ip\tau} + t_{ip\tau} \tag{2}$$

$$S_{0p\tau} + t_{ip\tau} \leq S_{jp\tau}, \quad 0_{p\tau} \rightarrow i_{p\tau} \rightarrow j_{p\tau} \tag{3}$$

$$\sum_{i_p=1}^{n_p} r^{p}_{ik\tau} \leq R_{k\tau} \quad \forall p \in P_\tau \tag{4}$$

$$Tardiness_p = \max\left(0, C_{n_pp\tau} - D_{(n+1)p\tau}\right) \tag{5}$$

$$C_{ip\tau} \leq S_{jp\tau}, \quad i_{p\tau} \rightarrow j_{p\tau} \tag{6}$$

When more than one project are considered for planning with resource constraint, some of the resources are shared among the activities of all projects and these resources are termed here as sharing resources which need to process activities from more than one projects. In each HLP horizon τ, there are different number of MLP horizons $0 < \tau \leq \Gamma$, all the projects $p_\tau \in P_\tau$ and activities from different projects which starts in MLP horizon τ are combined to make a combined project activity diagram of projects. Some activities of the multi-projects shares the resources due to which these activities of multi-projects have waiting time on the shared resources. Multi projects are planned and scheduled with an aim to minimize the tardiness of projects as indicated in Equation (1). In multi project planning and scheduling, the completion time of activities of the projects on the shared resources have constraints as given in Equation (7). Equation (7) indicates that the completion time of an activity of a project which is performed on a shared resource depends on the start time of this activity on the shared resource and the processing time of activity in a sequence of activities on the shared resource.

$$S_{ip(X_k)k\tau} + T_{ip(X_k)k\tau} \leq C_{ip(X_k)k\tau} \tag{7}$$

where, X_k shows the position of an activity in the sequence $\pi_k^{(i_p)}$ on a sharing resource $k \in R_{k(sh)\tau}$ in the MLP horizon τ. The constraint shown in Equation (8) shows that in the combined project, when an activity is performed on a resource, the starting time the activity is greater or equal to the starting time of the same activity when it is performed without considering it in the combined project and it is considered as an activity of an individual project. Equation (9) shows the start time constraint of an activity of project in combined project. It indicates two conditions. The first condition shows that the start time of an activity $i^c_{pk\tau}$ of project $p_\tau \in P_\tau$ on the combined project is greater or equal to the completion time of an activity $j^c_{qk\tau}$ of project $q_\tau \in P_\tau$, when both $i^c_{pk\tau}$ and $j^c_{qk\tau}$ are performed on the sharing resource $k \in R_{k(sh)\tau}$ at position $X_{k\tau}$ and $Y_{k\tau}$ respectively such that $X_{k\tau} \geq Y_{k\tau} + 1$ i.e., activity $j^c_{qk\tau}$ is performed before activity $i^c_{pk\tau}$ and these activities are sequenced to process on the sharing resource in consecutive positions in the sequence $\pi_k^{(i_p)}$. The second condition shows that the start time of an activity $i^c_{pk\tau}$ of project $p_\tau \in P_\tau$ on the combined project is greater or equal to the start time of the same activity $i^c_{pk\tau}$ of project $p_\tau \in P_\tau$, when $i^c_{pk\tau}$ is performed on the sharing resource $k \in R_{k(sh)\tau}$ at position $X_{k\tau} = 1$ in the sequence $\pi_k^{(i_p)}$ on the shared resource or $i^c_{pk\tau}$ is not performed on the shared resource. The constraint shown in Equation (10) shows the completion time of the activity $j^c_{qk\tau}$.

$$S_{ip(X_k)k\tau} \geq S_{ip\tau}, \quad \forall i^c_{pk\tau}, \ \forall P_\tau \tag{8}$$

$$S_{ip(X_k)k\tau} \geq \begin{cases} C_{jq(Y_k)k\tau} & if, \ X_{k\tau} \geq Y_{k\tau} + 1, \ and \\ S_{ip\tau} & if, \ X_{k\tau} = 1, and, k \in R_{k(sh)\tau} \ or \end{cases}$$

$$\begin{matrix} k \in R_{k(sh)\tau} \\ k \notin R_{k(sh)\tau} \end{matrix}, \quad \forall p_\tau \wedge q_\tau \in P_\tau \tag{9}$$

where,

$$C_{jq(Y_k)k\tau} \geq S_{jq(Y_k-1)k\tau} + t_{jq(Y_k-1)k\tau} \tag{10}$$

The constraint shown in Equation (11) shows two conditions for the process time $T_{ip(X_k)k\tau}$ of an activity $i^c_{pk\tau}$ of combined project. The first condition is applied when the activity $i^c_{pk\tau}$ is not performing on the sharing resource and it indicates that the processing time $T_{ip(X_k)k\tau}$ of an activity $i^c_{pk\tau}$ is greater or equal to the sum of start time of the activity and the processing time of the activity which are based on the project activity diagram of the individual project. The second condition shown in Equation (11) shows that the processing time $T_{ip(X_k)k\tau}$ of an activity $i^c_{pk\tau}$ is greater or equal to the sum of the start time of the same activity when it is performed on a sharing resource at position $X_{k\tau}$ in the sequence $\pi_k^{(i_p)}$. Equation (12) presents the resource constraint of sharing resources when activities from multiple projects are performed on it.

$$T_{ip(X_k)k\tau} \geq \begin{cases} S_{ipk\tau} + t_{ipk\tau} & if, \ k \notin R_{k(sh)\tau} \\ S_{ip(X_k)k\tau} + t_{ipk\tau} & if, \ k \in R_{k(sh)\tau}, \end{cases}$$

$$\forall p_\tau \wedge q_\tau \in P_\tau \tag{11}$$

$$\sum_{p=1}^{P} \sum_{i=1}^{n_p} r^p_{ik\tau} \leq R_k, R_k \in R_{k(sh)} \tag{12}$$

The constraint shown in Equation (13) shows the processing time of any activity of a partial project which is started in a planning horizon τ and it partially completed in the previous planning horizons, subject to the condition that, $S_{ipk\tau} + t_{ipk\tau} \geq \tau$. The condition, $S_{ipk\tau} + t_{ipk\tau} \geq \tau$, shows that when the activity $i^c_{pk\tau}$ starts in a planning horizon τ, its duration is more than the duration of planning horizon and therefore, it cannot be completed in the given planning horizon τ and therefore, a part of the activity is completed in the planning horizon τ and the remaining part of activity is completed in the next planning horizon. It can be seen from equation (13) that the process time $t_{ipk\tau}$ of activity $i^c_{pk\tau}$ in any MLP planning horizon $\tau*$ is the difference between the processing time of $t_{ipk\tau}$ with the time which has been spend to complete it partially in all previous MLP planning horizons of τ, i.e., $t^{\partial}_{ip(x-1)k\tau}$.

$$t_{ipk\tau*} = t_{ipk\tau} - \sum_{x=1}^{\tau} t^{\partial}_{ip(x-1)k\tau}, \quad \forall i^{\partial}_{pk\tau} = 1, 2, \ldots, n^{\partial}_{pk\tau} \tag{13}$$

where, $t^{\partial}_{ip(x-1)k\tau}$ is the processing time of an activity $i^{\partial}_{pk\tau}$ which is completed in the MLP horizon τ and $t_{ipk\tau}$ is the processing time of activity which is to perform in the planning horizon τ in a partial project. Equation (13) indicates that the processing time of an activity is updated in each planning horizon τ for partial projects. The processing time of an activity of the project is obtained by subtracting the total time i.e., $t^{\partial}_{ip(x-1)k\tau}$ of the partial activity in the previous planning horizons of τ.

III. DBR HEURISTIC FOR COORDINATED PLANNING AND SCHEDULING OF MULTI-PROJECTS IN ROLLING HORIZON

In the current research, higher level planning (HLP) and medium level planning (MLP) of multi-projects are integrated for multi-level planning of projects in rolling horizon. The proposed multi-level planning problem is composed of two parts which are name here as infinite capacity plan of projects for HLP planning horizons and finite capacity plan at MLP planning horizons. Figure. 2 illustrates the framework of the procedure of proposed DBR heuristic for coordinated planning and scheduling of multi projects in rolling horizon.

Figure. 3 shows the flow chart to show the procedure and detail of the proposed DBR heuristic for coordinated planning at HLP and scheduling at MLP of multi projects in the current research considering arrival of new projects during MLP planning horizons and HLP planning horizons. The step wise procedure of the proposed DBRH is explained in this section.

A. INFINITE CAPACITY PLAN FOR HIGHER LEVEL PLANNING (HLP)

The first step in the proposed DBRH for coordinated planning and scheduling of multi projects at HLP planning horizons is to make project plan at infinite capacity or resources. In the current research, first a rough plan based on infinite capacity of resources is prepared. Using this rough plan based on

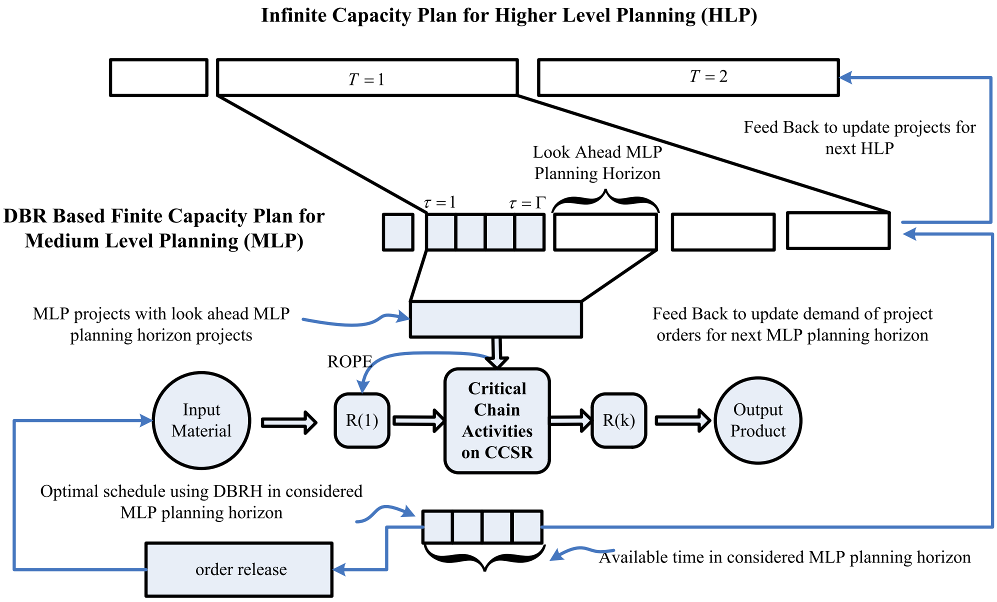


FIGURE 2. Framework of the proposed procedure of proposed DBR heuristic.

infinite capacity, projects are assigned to their most deserving HLP planning horizon based on their earliest start time, latest start time, material arrival time and due dates. In rough plan of infinite capacity, all the projects in the planning horizon are included in the order pool and they are assigned to each HLP horizons based on the material arrival time and due date constraints. Infinite capacity plan of multi projects is made through following steps.

Step 1.1: Find the latest start time of a project based on the activity durations of projects on resources is obtained taking into consideration the independent project critical path length CPL_{pT} of its activities, the shipping buffer time SB_{pT} and due date $D_{(n_p+1)T}$ of the project. The latest possible start time of projects to start in HLP is indicated in Equation (14). It can be seen from Equation (14) that all projects in any HLP must start processing before their latest start times to avoid any lateness.

$$LS_{0pT} = D_{(n_p+1)T} - \left(CPL_{pT}\right) - SB_{pT} \tag{14}$$

Step 1.2: Find the earliest start time of a project. Equation (15) illustrates the earliest start time of the projects on a resource in a HLP horizon. Equation (15) shows that the project can only start when the required material is available on the resource to start the first activity of the project and the resource is available to process the activity of the project.

$$ES_{0pT} = \max\left\{ST_{i_ppkT}, arv_{i_ppkT}^{material}\right\} \tag{15}$$

Step 1.3: Find the planned start time of projects. Equation (16) indicates the planned start time of projects based on maximum time between the earliest start time and latest start time of the project.

$$\begin{aligned} &\forall p_T \in P_T, \quad i_{pT} = 1 \\ &PST_{pT} = \max\left\{ES_{0pT}, LS_{0pT}\right\} \end{aligned} \tag{16}$$

Step 1.4: Insert the projects in different HLP planning horizons based on their planned start time. The rough plan base on infinite capacity is significant to arrange the projects in the HLP planning horizons to avoid their lateness and material constraint. It can decides the projects which are possible to start in different higher level planning horizons.

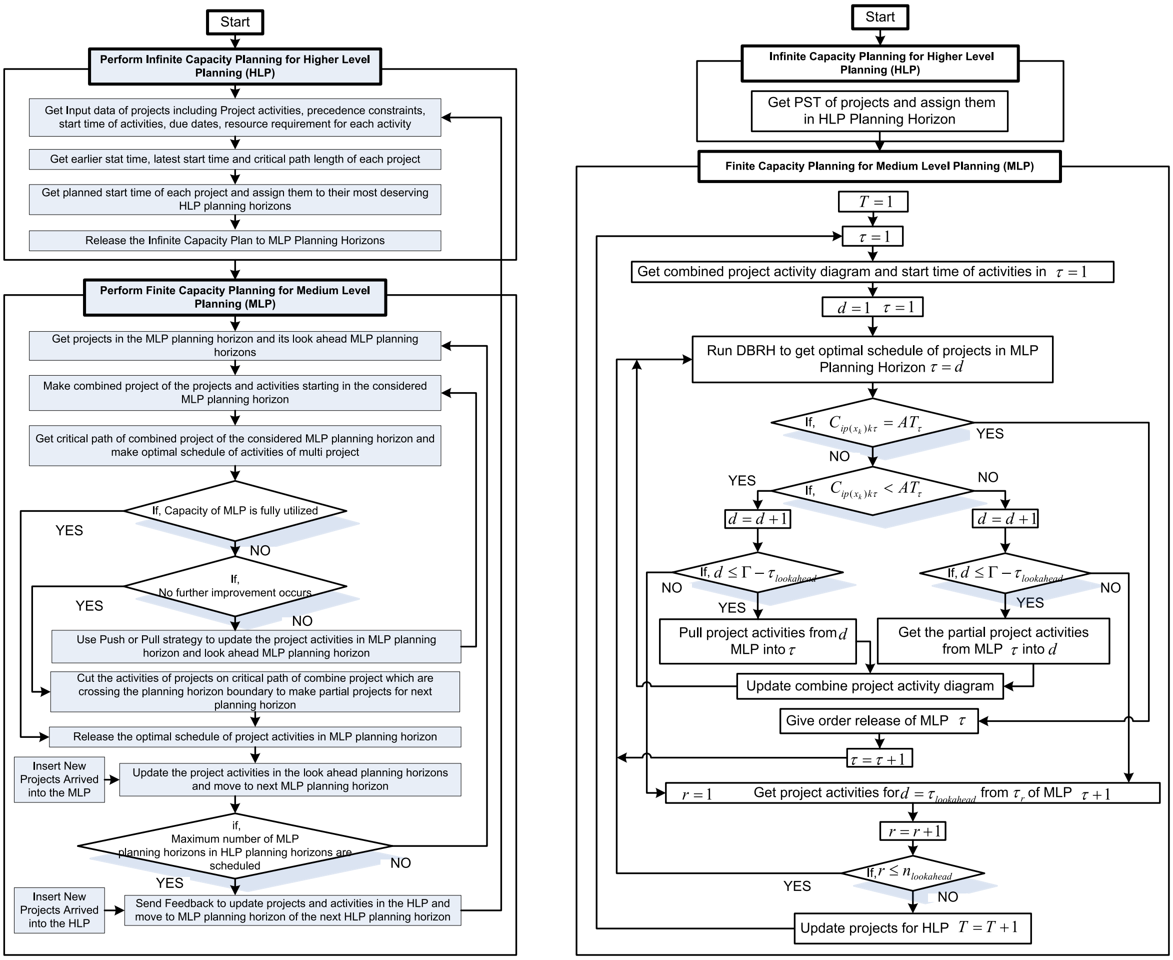
Step 1.5: Release the HLP plan of multi projects to the corresponding MLP planning horizons ahead of them.

B. FINITE CAPACITY PLAN FOR MEDIUM LEVEL PLANNING (MLP)

The projects which starts in a MLP planning horizon are combined to make their combined project activity diagram. It also includes the activities of the projects which have start time in the considered MLP horizon. Drum buffer rope mechanism which is the application of theory of constraint is utilized in the current research to make the plan for the projects in the MLP planning horizon along with the project activities of the look ahead MLP planning horizons. The plan for a MLP horizon is made in advance by one MLP planning horizon and the time of one MLP horizon is considered as time buffer for the next MLP horizon. Current research introduces a drum buffer rope based heuristic for multi-level rolling horizon planning of multi-projects which is explained in here. The step by step procedure of finite capacity plan for medium level planning (MLP) planning horizons in explained in this section.

Step 2.1: Begin with $\tau = 1$ MLP planning horizon of HLP and get the projects and project activities starting in the considered MLP and look ahead planning horizon.

Step 2.2: Make combined project of the project activities considered in **Step 2.1**. Make partial affective schedule of projects. A project schedule is considered as partially affective schedule if none of project activities



Procedure proposed DBRH for coordinated planning and scheduling of multi projects in rolling horizon

Detail of DBRH for coordinated planning and scheduling of multi projects in rolling horizon

FIGURE 3. Flow chart to show the procedure and detail of the proposed DBRH for coordinated planning and scheduling of multi projects in rolling horizon.

belonging from different projects can be started earlier without changing the schedule of activities of different projects on a resource or resources in the combined project activity schedule.

Step 2.3: Get critical path of combined project using next following relation and next following chain as explained below:

The Next-Following Relation and Next-Following Chains

$\pi^{(ip)}_{R_k\tau}$ shows a sequence of activities of all projects $p_\tau \in P_\tau$ on all resources $R_{k\tau}$ and gives one solution of the sequence of activities from all projects P_τ in MLP planning horizon τ, on all resources considering combined project activity diagram.

Suppose $i^c_{pk\tau}$ and $j^c_{ql\tau}$ are the two activities in a project schedule $\pi^{(ip)}_{R_k\tau}, j^c_{ql\tau}$ next follows activity $i^c_{pk\tau}$ if and only if,

A) $S_{jq(X_l)\tau} = C_{ip(X_k)\tau}$, i.e., the starting time of activity $j^c_{ql\tau}$ is equal to the completion time of activity $i^c_{pk\tau}$ for a project $p_\tau = q_\tau \in P_\tau$ in the combined project, $k \wedge l \in R_{k\tau}$.

B) $\left(i^c_{pk\tau} \to j^c_{ql\tau}\right) \vee \left(i^c_{pk\tau} \to j^c_{qk\tau}\right)$, i.e., either $i^c_{pk\tau}$ precedes $j^c_{ql\tau}$ for the same project $p_\tau = q_\tau \in P_\tau$ and might be on different resources $k \in R_{k\tau}, l \in R_{k\tau}$, or $i^c_{pk\tau}$ precedes $j^c_{ql\tau}$ at the same resource $k \in R_{k\tau}$ and can belongs from different projects $p_\tau \in P_\tau, q_\tau \in P_\tau$, in the schedule $\pi^{(ip)}_{R_k\tau}$.

The next following chain $C^{\pi c}_{ip\tau}$ of an activity $i^c_{pk\tau}$ in a schedule $\pi^{(ip)}_{R_k\tau}$ of next following activities $\forall i_{p\tau} = 1, 2, \ldots., n_{p\tau}, \forall P_\tau$, connecting $i^c_{pk\tau}$ to an initial activity without predecessor. The next following chain of an activity $i^c_{pk\tau}$ is the longest path from $S_{0p\tau}$ to the completion time of activity $i^c_{pk\tau}$, i.e., $C_{ip(X_k)k\tau}$. More specifically,

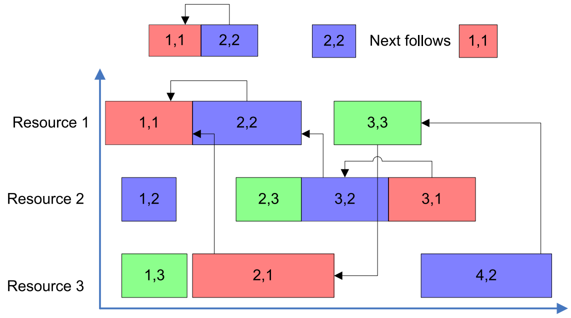


FIGURE 4. Sequence of activities of multi-projects on CCSR with next following activities and next following chains.

a) Each activity except for the one starting the schedule on a resource, i.e., at position $X_k = 1, \forall k \in R_{k\tau}$, next-follows exactly one other activity in the schedule and
b) For each activity except, $i^c_{pk\tau}$, the sequence contains exactly one activity that next-follows it.

Consider 3 projects have activities which are performed on 3 different capacity constraint sharing resources. One of the possible sequence of activities of these projects on different CCSR is indicated in Figure. 4. It can be seen from Fig. 4 that, the second activity of project 2 next follows the first activity of project 1 on resource 1. Moreover, the third activity of the project 1 which is performed on resource 2 next follows the third activity of project 2 which is performed on resource 2. Furthermore, the next following chains are also presented in Figure. 4 with the arrows connecting activities of different projects to the next following activities considering all resources. It can be seen that one of the next following chain is represented by connecting the fourth activity of project 2, third activity of project 3, second activity of project 1 and first activity of project 1.

Properties of Next-Following Chains

Following two properties are defined for the next following chain.

A) For any project activity $i^c_{pk\tau}$ in the combined project, there exists at least one next following chain.
B) The next following chain of any project activity $i^c_{pk\tau}$ corresponds to the longest length chain from $S_{0p\tau}$ to the activity $i^c_{pk\tau}$, i.e., $f_{ip(X_k)k\tau}$

$$f_{ip(X_k)k\tau} = \sum_{p=1}^{N}\sum_{i=1}^{n_p} T_{ipk\tau} \times X_{ip\tau}$$

where,

$$X_{ip\tau} = 1,\ if\ i \in C^{\pi c}_{ip\tau},$$
$$X_{ip\tau} = 0,\ otherwise$$

Step 2.5: Apply local search on the activities appearing on the next following chain using neighborhood structure. The neighborhood structure proposed in the current research is explained below:

Neighborhood Structure for Local Search of Project Activity Schedules

In the proposed DBRH, in each MLP, the projects which are started, are considered to schedule first to determine the projects which are tardy. The proposed neighborhood structure in DBRH is designed to reduce the tardiness of projects and make an optimal schedule of multi-project activities which can give minimum value of the tardiness of projects. The neighborhood structure defined here is used to determine the activities which are more affective to schedule in order to reduce the tardiness of the projects. The search neighborhood is identified by single schedule and set of transitions. Each transition corresponds to a change in the sequence of selected activities. The transitions are designed to operate on next-following chains in the semi-active schedule of activities of the projects in MLP. The allowed activities are exchanged between pairs of next following activities on the same resource on a few critical next following chains. The neighborhood structure follows following steps:

Step 2.5.1: In the current schedule $\pi^{(ip)}_{R_k\tau}$, determine the set of critical tardy projects CTP_τ. It contains the tardiest projects from the set of projects. For each project $p_\tau \in CTP_\tau$, add its last activity to the critical final activities set CFA_τ

Step 2.5.2: Find a next following chain $C^{\pi c}_{ip\tau}$ passing through each activity $i^c_{pk\tau} \in CFA_\tau$. In each of these chains, identify the target activities, i.e., those activities of projects which do not next follow their predecessors in the same project (i.e., $S_{ip(X_k)k\tau} > f_{jp(X_k)k\tau}$), $\left(i^c_{pk\tau} \rightarrow j^c_{pl\tau}\right)$, $(k \wedge l) \in R_{k\tau}$. The collective set of target activities is labeled as TA_τ. These activities start later than the completion time of their predecessor activities.

Step 2.5.3: The search neighborhood $N(\pi^{(ip)}_{R_k\tau})$ is constructed by exchanging a target activity $j^c_{ql\tau} \in TA_\tau$ with its predecessor $i^c_{pk\tau} \in TA_\tau$, i.e., $\left(i^c_{pk\tau} \rightarrow j^c_{ql\tau}\right)$ at the same resource $(k = l) \in R_{k\tau}$. This can change the sequence of the activities by changing the position of target activity with its predecessor activity on the same resource.

If, more than one next-following chain exists for an activity in **Step 2.5.2**, only one of them needs to be considered. If a target activity $i^{c}_{pk\tau} \in TA_{\tau}$ next follows two activities, i.e., $j^{c}_{pl\tau}$ and $j^{c}_{qk\tau}$, then the activity of the same project i.e., $j^{c}_{pl\tau}$ is considered in the next following chain, instead of the activity on the same resource, i.e., $j^{c}_{qk\tau}$.

Step 2.6: Apply Local search to find the optimal schedule of project activities on critical chain of the combined project. The rules for selection of transition is explained below:

Rules for Selection of Transitions

Basic Tabu search method [66]–[69] is used in the proposed DBRH. Tabu list is prepared by first-in, first-out (FIFO) rule with $n+1$ nodes. Each time a transition is selected for pair-wise activity exchange, the earlier of the two activities is added to the tail of the Tabu list before the exchange takes place. The node at the end of the list is dropped once the exchange takes place. All the activities in the Tabu list are forbidden from left shifting (i.e., they are not allowed to exchange with the activities which are earlier) unless it can improve the current best solution. This can serves to prevent the transitions that might reverse the recent transition of activities and lead to cycling. This kind of "memory" can prevent the proposed algorithm to trap in the local optima. The proposed algorithm chooses the transitions which can give minimum value of the tardiness of projects. The procedure of the algorithm is described as under:

Step 2.6.1: Set iterations, $z = 0$, generate the initial semi-active schedule of projects in the considered iteration, i.e., $\pi^{(ip)^{z}}_{R_k\tau}$, set $\pi^{(ip)^{z}}_{R_k\tau}$ to $\pi^{(ip)}_{R_k\tau}(o)$

Step 2.6.2: Identify the set of target activities TA_{τ}. Construct the set TAN of all transitions that are not forbidden by the Tabu list.

Step 2.6.3: Calculate the total tardiness of all schedules resulting from the transitions in TAN. Select the transition t which gives minimum value of $Tardiness_{p\tau}$.

Step 2.6.4: Perform the transition t to transform $\pi^{(ip)^{z}}_{R_k\tau}$ into $\pi^{(ip)^{z+1}}_{R_k\tau}$. Update the Tabu List.

If, $TTardiness_{p\tau\pi(z+1)(t)} < TTardiness_{p\tau\pi(o)(t)}$, set $\pi^{(ip)^{z+1}}_{R_k\tau}$ to $\pi^{(ip)}_{R_k\tau}(o)$. If, termination condition is met, Stop and Go to **Step 2.7**.

Otherwise, set, $z = z+1$ and got to **Step 2.6.2.**

Step 2.7: If, capacity of MLP planning horizon is fully utilized in the optimal schedule $\pi^{(ip)}_{R_k\tau}(o)$, i.e., in the schedule $\pi^{(ip)}_{R_k\tau}(o)$ which is obtained in **Step 2.6**,

If, $C_{ip(x_k)k\tau} = AT_{\tau}$, Go to **Step 2.8**.

Else,

If, No further improvement in schedule can occurs

Cut the activities of projects on critical path of combine project which are crossing the planning horizon boundary to make partial projects for next planning horizon using Equation (13) and Go to **Step 2.8**.

Else,

Use Push or Pull strategy to update the project activities in considered MLP planning horizon and look ahead MLP planning horizon and Go to **Step 2.2**.

Step 2.8: Release the project schedule in the considered MLP planning horizons τ.

Insert new projects arrived into the MLP Planning horizon and update the project activities in the look ahead planning horizons and move to $\tau = \tau + 1$ MLP planning horizon for scheduling of activities.

If, Maximum number of MLP planning horizons in HLP planning horizons are scheduled.

Insert new projects arrived into the HLP Planning horizon.

Send Feedback to update projects and activities in the considered HLP T and move to $\tau = 1$ MLP planning horizon of the $T = T + 1$, HLP planning horizon and go to **Step 1.1**.

Else, Go to **Step 2.1**.

IV. COMPUTATIONAL EXPERIMENT AND RESULTS

In this section, the performance of the proposed DBRH, based on different problem instances is tested. The considered problem is novel in literature and is addressed for the first time here, therefore, simple problems instances are elaborated first to describe the results in detail. In addition to these simple problem instances, two different type of problems are considered which are described in this section to illustrate their input data.

A. EXPERIMENTS BASED ON SIMPLE PROBLEMS INSTANCES

1) INPUT DATA

Current research problem has different parameters which can create different problem instances. These parameters include the number of HLP planning horizons, number of MLP planning horizons in each HLP, Number of projects and number of activities in each project. Each problem is designed here to randomly take the number of MLP planning horizons in each HLP in the range of (2, 10). Moreover, the types of projects which arrives in the HLP planning horizon for each problem instance are randomly taken from the range of (1, 10). The number of activities of each type of project are considered to vary between the range of (3, 10). The due dates of the projects is assumed as sum of the process time of all activates in the single project. There are 5 different problem instances created here which are illustrated in Table 1.

TABLE 1. Type of problems with their design parameters.

Problem Instances Data

Problem	No of HLP	No of MLP in HLP	Duration of each MLP	Type of Projects	Number of activities in projects
1	2	3	10	2	4, 3
2	18	6	5	4	5, 7, 10, 5
3	5	2	12	5	5, 7, 10, 5, 10
4	2	3	8	7	10, 20, 30, 25, 30, 15, 30
5	2	6	5	4	4, 3, 3, 4

Input data for Problem 1

Project Types	Due date	Activities	Arrival time of activity	Process time of activity	Shipping buffer of activity	Precedence constraint of project	Available capacity of resources									
							1	2	3	4	5	6	7	8	9	10
							10	10	10	10	10	10	10	5	9	2
							Capacity Requirement of resource									
							1	2	3	4	5	6	7	8	9	10
Project 1	30	1	2	3	1	1>(2,3); 2>4;3>4	0	0	0	0	1	2	2	1	3	2
		2	3	2	1		0	0	0	0	0	2	0	0	3	1
		3	4	5	3		1	1	3	3	0	0	2	0	3	0
		4	5	2	4		0	0	0	0	0	0	9	0	0	0
Project 2	50	1	4	1	9	1>2;2>3	1	1	1	2	1	1	1	1	1	1
		2	4	4	1		0	0	0	0	1	0	0	2	1	2
		3	4	2	4		1	1	2	2	0	0	0	0	0	0

Input data for Problem 2

Project Types	Due date	Activities	Arrival time of activity	Process time of activity	Shipping buffer of activity	Precedence constraint of project	Available capacity of resources		
							1	2	3
							50	50	10
							Capacity Requirement of resource		
							1	2	3
1	15	1	0	40	1	1>2; 2> (3, 4); 3>5; 4>5	10	10	1
		2	3	10	2		10	10	1
		3	1	10	1		5	14	0
		4	4	30	1		20	10	10
		5	10	20	1		15	15	2
2	40	1	1	20	1	1>2; 2>(3, 4, 5); 3>(4, 6); 4>(5, 6); 5>6; 6>7	10	5	1
		2	14	40	2		12	18	0
		3	10	150	1		15	14	0
		4	10	150	2		5	20	0
		5	12	10	3		25	5	0
		6	30	10	4		5	45	5
		7	30	20	5		0	10	5
3	100	1	0	20	1	1>(2, 3); 2>4; 3>(6, 7); 4>5; 5>8; 6>8; 7>8; 8>9; 9>10	5	5	0
		2	8	60	1		8	10	2
		3	8	50	1		10	10	2
		4	30	40	1		15	5	1
		5	5	10	1		4	12	3
		6	0	12	0		7	12	0
		7	35	10	10		23	20	1
		8	2	10	1		10	5	0
		9	2	30	1		5	3	0
		10	2	12	4		30	2	3
4	100	1	0	15	2	1>(2, 3); 2>3; 3>(4, 5)	5	10	1
		2	14	20	3		5	10	1
		3	30	11	3		5	10	1
		4	50	10	4		5	10	1
		5	20	15	1		5	10	1

Input data for Problem 3

Project Type	Due date	Activities	Arrival time of activity	Process time of activity	Shipping buffer of activity	Precedence constraint of project	Available capacity of resources		
							1	2	3
							50	30	10
							Capacity Requirement of resource		
							1	2	3
1	15	1	0	4	1	1>2; 1>(3,4); 3>5; 4>5	10	2	1
		2	3	3	1		10	0	3
		3	6	2	1		0	5	6
		4	9	7	1		15	5	1
		5	10	3	1		15	15	2

TABLE 1. ***(Continued.)*** **Type of problems with their design parameters.**

2	40	1	15	2	1	1>2; 1>(3, 4, 5); 2>(4, 6); 4>(5, 6); 5>6; 6>7	10	5	1
		2	17	4	1		12	10	0
		3	17	5	1		15	7	0
		4	20	4	1		5	10	0
		5	12	3	1		25	5	0
		6	30	7	1		5	15	5
		7	30	1	1		0	10	5
3	100	1	0	2	1	1>(2,3); 2>4; 3>(6, 7); 4>5; 5>8; 6>8; 7>8; 8>9; 9>10	5	5	5
		2	8	6	1		20	5	1
		3	8	8	5		0	4	2
		4	30	4	1		15	5	1
		5	30	5	1		4	12	3
		6	30	6	1		7	12	0
		7	35	10	10		23	10	1
		8	37	10	1		10	0	0
		9	39	7	1		5	3	0
		10	41	12	1		30	0	3
4	50	1	20	4	2	1>(2, 3); 2>3; 3>(4, 5)	5	8	2
		2	24	10	3		5	4	1
		3	30	7	3		15	3	1
		4	40	10	4		0	4	6
		5	50	2	1		20	4	4
5	80	1	1	2	0	1>(2,3); 2>4; 3>(6, 7); 4>5; 5>8; 6>8; 7>8; 8>9; 9>10	5	5	0
		2	1	6	8		8	10	2
		3	1	5	9		10	10	2
		4	1	4	30		15	5	1
		5	1	10	35		4	12	3
		6	0	4	45		7	7	0
		7	10	10	55		23	6	1
		8	1	5	60		10	5	0
		9	1	7	65		5	3	0
		10	4	8	70		15	2	3

Input data for Problem 4

Project Type	Due date	Activities	Arrival time of activity	Process time of activity	Shipping buffer of activity	Precedence constraint of project	Available capacity of resources		
							1	2	3
							50	70	40
							Capacity Requirement of resource		
							1	2	3
1	10	1	1	3	0	1>2; 2>3	9	20	15
		2	0	4	1		12	8	10
		3	2	2	1		10	20	15
2	20	1	2	3	1	1>(2,5); 2>3; 3>4; 4>5	15	20	10
		2	1	2	0		10	5	10
		3	0	4	0		20	10	8
		4	3	1	1		6	12	18
		5	1	3	1		13	9	21
3	30	1	2	4	1	1>(2, 3, 5); 2>(3, 6); 3>4, 6); 4>5; 5>6	12	3	25
		2	1	2	0		6	5	10
		3	0	2	1		20	13	11
		4	2	3	0		9	12	7
		5	2	4	1		23	18	22
		6	1	1	0		4	15	10
4	25	1	1	1	1	1>2; 2>(3, 4); 3>4	5	14	19
		2	3	2	0		16	21	6
		3	2	3	1		20	15	5
		4	0	4	0		8	13	4
5	30	1	1	2	1	1>2; 2>3; 4>5	10	10	10
		2	2	3	0		15	20	15
		3	4	4	1		5	10	20
		4	0	0	1		20	10	15
6	15	1	0	0	1	1>(2, 3); 2>3	15	5	5
		2	0	4	0		10	5	25
		3	1	2	1		10	15	15
7	30	1	1	2	0	1>2; 2>(3, 4); 3>(4, 5); 4>5	10	5	10
		2	1	1	0		5	15	10
		3	0	3	1		10	8	10
		4	4	2	0		25	5	10
		5	3	2	0		15	20	6

TABLE 1. *(Continued.)* Type of problems with their design parameters.

Input data for Problem 5

Project Type	Due date	Activities	Arrival time of activity	Process time of activity	Shipping buffer of activity	Precedence constraint of project	Available capacity of resources									
							1	2	3	4	5	6	7	8	9	10
							10	10	10	10	10	10	10	5	9	2
							Capacity Requirement of resource									
							1	2	3	4	5	6	7	8	9	10
1	10	1	4	3	1	1>(2,3); 2>4; 3>4	0	0	0	0	1	2	2	1	0	0
		2	3	2	1		0	0	0	0	0	2	0	0	3	1
		3	5	5	3		1	1	3	2	0	0	2	0	3	0
		4	2	2	4		0	2	0	0	0	0	6	0	0	0
2	20	1	6	1	9	1>2; 2>3	1	1	1	2	1	1	1	1	1	1
		2	4	4	1		0	1	0	1	2	0	0	2	1	2
		3	1	2	4		1	1	2	2	0	1	2	0	0	0
3	10	1	2	2	6	1>2; 2>3	2	1	1	2	1	1	1	0	1	1
		2	1	3	5		0	1	0	3	1	1	0	1	1	2
		3	0	1	2		0	2	1	1	0	0	1	3	0	0
4	30	1	4	3	1	1>(2, 3); 2>4; 3>4	0	0	0	0	1	2	2	1	0	0
		2	3	2	1		0	0	0	0	0	2	0	0	3	1
		3	5	5	3		1	1	3	2	0	0	2	0	3	0
		4	2	2	4		0	1	0	0	0	0	6	0	0	0

The considered 5 problems are solved using proposed DBRH. The performance of the proposed DBRH algorithm is tested with famous optimization methods including Standard Tabu Search algorithm (TS), Standard Genetic Algorithm (GA), Tabu Search with Priority Rule of Most Tardiest Project (TS-MTP), Genetic Algorithm with Priority Rule of Most Tardiest Project (GA-MTP). All the algorithms including DBRH, TS, GA, TS-MTP and GA-MTP are coded in Matlab and Run on Intel Dual Core I 7 computing machine.

2) COMPARISON OF RESULTS

The performance of the proposed DBRH algorithm is tested based on the considered designed problems and the performance is measured by comparing the total tardiness of projects in each problem. Each of the algorithm including, TS, GA, TS-MTP and GA-MTP are run for several times to obtain the best results of the considered problems. For each problem, 50 of the best results obtained from each of these comparing heuristics (i.e., TS, GA, TS-MTP, GA-MTP) are considered to compare with the results obtained from DBRH algorithm for each problem. In order to increase the robustness in comparison of results, 50 best results of each TS, GA, TS-MTP and GA-MTP are combined together to make population of best 200 (i.e., 4 times 50) results for each problem. Out of these 200 results the best of the 10 results are sorted and compared with the results of the proposed DBRH for each considered problem. The considered objective of the problem is minimizing objective and in order to compare the results with best results of the TS, GA, TS-MTP and GA-MTP, percentage average deviation (PAD) is computed which is described in Equation (17). Moreover, percentage difference of the tardiness obtained from DBRH and the average value of tardiness of the other comparison heuristics is computed using Equation (18).

$$PAD = \frac{1}{10} \times \sum_{s=1}^{10} \left[\frac{Tardiness_{DBRH} - (Tardiness_{CH})_s}{Tardiness_{DBRH}} \right] \tag{17}$$

$$PD = \frac{[Tardiness_{DBRH} - AT_{CH}]}{Tardiness_{DBRH}} \tag{18}$$

where,

$$AT_{CH} = \frac{1}{10} \sum_{s=1}^{10} (Tardiness_{CH})_s \tag{19}$$

where, *PAD* represents the average deviation in the tardiness value. ($Tardiness_{CH}$) shows the best of the tardiness value obtained from the comparing heuristics (CH) including TS, GA, TS-MTP and GA-MTP and *s* indicates any solution from the best 10 solutions which are taken from the total of 200 best solutions obtained from the comparing heuristics. The tardiness values obtained from DBRH and CH for problems [1, 2, 3, 4, 5] are [−31, 796, 76, 21, 50] and [−31, 812.5, 118, 21.4, 49.4] respectively. In addition, PD values and average PAD of tardiness from problem [1, 2, 3, 4, 5] are [0, 2.03, 35.6. 1.89, −1.2] and [0, 2.07, 55.3, 1.9, −1.2] respectively.

It can be seen from these results that, the value of tardiness of projects obtained from proposed DBRH for different problems are significantly better as compared to the tardiness values obtained from the best results obtained from the other comparing heuristic methods including TA, GA, TS-MTP and GA-MTP. For instance, it can be seen from these results that for problem Type 3, the tardiness value of projects obtained from DBRH is 76 while the average value of the best results of the tardiness of comparing heuristics is 118. These results indicate that there is 35.6 percent difference in the tardiness results which is a significant number. These results indicate that the proposed DBRH is better as compared to the comparing heuristics, i.e., CH on the basis of problem Type 3. In addition, the average percentage deviation (PAD) of the Problem type 3 is 55.3 which is a significantly large value. These results indicate that the multi-level project plan of multi-projects proposed by the DBRH is optimal and it can reduce the tardiness of multi-projects in rolling horizon planning considering the resource constraints. The results

TABLE 2. Multi-level planning results of constraint resource multiple projects in Problem Type 3.

HLP	MLP	Activity Schedule	
		DBRH	Best of all CH results
1	1	(1/2,1) : 6 --> 10; (1/4,1) : 10 --> 12; (1/3,1) : 10 --> 12; (3/1,1) : 1 --> 4; (3/3,1) : 4 --> 10; (3/7,1) : 10 --> 12; (3/2,1) : 4 --> 10; (3/2,2) : 12 --> 13; (5/2,1) : 6 --> 13; (5/1,1) : 1 --> 4; (1/1,1) : 1 --> 6;	(1/1,1) : 1 --> 6; (3/1,1) : 1 --> 4; (5/1,1) : 1 --> 4; (1/2,1) : 6 --> 10; (1/3,1) : 10 --> 12; (3/2,1) : 4 --> 11; (5/2,1) : 4 --> 11; (1/4,1) : 11 --> 13; (5/3,1) : 11 --> 13; (5/4,1) : 12 --> 13; (3/3,1) : 6 --> 10;
	2	(1/4,2) : 13 --> 19; (2/1,1) : 15 --> 18; (1/3,2) : 13 --> 14; (2/2,1) : 18 --> 23; (2/3,1) : 23 --> 24; (1/5,1) : 24 --> 25; (4/1,1) : 20 --> 24; (3/7,2) : 13 --> 24; (3/4,1) : 19 --> 20; (3/4,2) : 24 --> 25; (3/6,1) : 14 --> 15; (5/3,1) : 13 --> 14;	(2/1,1) : 15 --> 18; (2/2,1) : 18 --> 23; (1/3,2) : 13 --> 14; (2/3,1) : 23 --> 24; (1/4,2) : 13 --> 19; (5/3,2) : 13 --> 17; (1/5,1) : 24 --> 25; (5/4,2) : 17 --> 21; (4/1,1) : 21 --> 24; (3/3,2) : 19 --> 21; (3/4,1) : 23 --> 25; (3/7,1) : 21 --> 23;
2	1	(2/3,2) : 25 --> 30; (1/5,2) : 30 --> 33; (4/1,2) : 25 --> 27; (2/4,1) : 33 --> 37; (4/2,1) : 27 --> 36; (3/7,3) : 25 --> 32; (3/4,3) : 33 --> 36;	(2/3,2) : 25 --> 30; (2/4,1) : 30 --> 35; (2/5,1) : 35 --> 36; (1/5,2) : 35 --> 37; (4/1,2) : 25 --> 28; (4/2,1) : 28 --> 35; (4/2,2) : 36 --> 37; (3/4,2) : 25 --> 28; (5/6,1) : 28 --> 30; (5/7,1) : 30 --> 35; (3/7,2) : 28 --> 30; (3/7,3) : 36 --> 37;
	2	(2/4,2) : 37 --> 38; (2/5,1) : 38 --> 42; (2/6,1) : 42 --> 48; (4/3,1) : 41 --> 48; (5/4,2) : 37 --> 41; (3/6,2) : 41 --> 42; (3/6,3) : 48 --> 49; (5/4,1) : 37 --> 38; (4/2,2) : 38 --> 41;	(2/5,2) : 37 --> 40; (1/5,3) : 37 --> 38; (2/6,1) : 40 --> 48; (4/2,3) : 38 --> 43; (5/5,1) : 48 --> 49; (4/3,1) : 43 --> 48; (5/6,2) : 38 --> 40; (5/7,2) : 48 --> 49; (3/7,4) : 40 --> 49;
3	1	(2/6,2) : 49 --> 51; (4/3,2) : 49 --> 52; (2/7,1) : 51 --> 53; (4/4,1) : 53 --> 61; (3/6,4) : 53 --> 57; (3/5,1) : 57 --> 61; (5/3,2) : 52 --> 53; (4/5,1) : 53 --> 56; (4/2,3) : 51 --> 52;	(2/7,1) : 49 --> 51 (5/5,2) : 51 --> 61; (4/3,2) : 49 --> 54; (4/4,1) : 54 --> 60; (4/5,1) : 54 --> 57; (5/7,3) : 49 --> 51; (5/7,4) : 60 --> 61; (3/7,5) : 57 --> 61;
	2	(4/4,2) : 61 --> 67; (3/5,2) : 61 --> 63; (5/3,3) : 63 --> 67; (5/5,1) : 67 --> 73; (3/8,1) : 63 --> 72; (5/7,1) : 67 --> 72; (5/6,1) : 72 --> 73;	(4/4,2) : 61 --> 69; (5/7,5) : 61 --> 72; (3/5,1) : 69 --> 73 (3/7,6) : 61 --> 63;
4	1	(5/5,2) : 73 --> 78; (3/8,2) : 73 --> 75; (5/7,2) : 73 --> 84; (5/6,2) : 78 --> 81; (3/9,1) : 78 --> 85;	(5/8,1) : 73 --> 79; (5/9,1) : 79 --> 84; (3/5,2) : 73 --> 75; (3/6,1) : 75 --> 82; (3/8,1) : 82 --> 84;
	2	(5/7,3) : 85 --> 89; (5/8,1) : 89 --> 95; (3/9,2) : 85 --> 86; (5/9,1) : 95 --> 96; (3/10,1) : 89 --> 97;	(5/9,2) : 85 --> 88; (5/10,1) : 88 --> 96; (3/8,2) : 85 --> 94; (3/9,1) : 94 --> 96;
5	1	(5/9,2) : 97 --> 104; (5/10,1) : 104 --> 108; (3/10,2) : 97 --> 102;	(5/10,2) : 97 --> 101; (3/9,2) : 97 --> 103; (3/10,1) : 103 --> 108;
	2	(5/10,2) : 109 --> 117;	(3/10,2) : 109 --> 117;

for Problem Type 5 shows the tardiness value of projects as 50 while the average tardiness value of the projects obtained from the comparing heuristics is 49.4 which is very close to the tardiness obtained from DBRH. These results indicate that the results obtained from the comparing heuristics are better as compared to the results obtained from DBRH with minor value. However, the results of most of the considered problems indicate the better performance of the proposed DBRH as compared to the results obtained from comparing heuristics.

The multi-level planning results of multi-projects in rolling horizon for Problem Type 3 is illustrated in Table 2. The schedule of project activities which is obtained from DBRH and the best schedule obtained from the comparing heuristics is also presented in Table 2. The graphical representation of the planning results of Problem Type 3 at HLP1

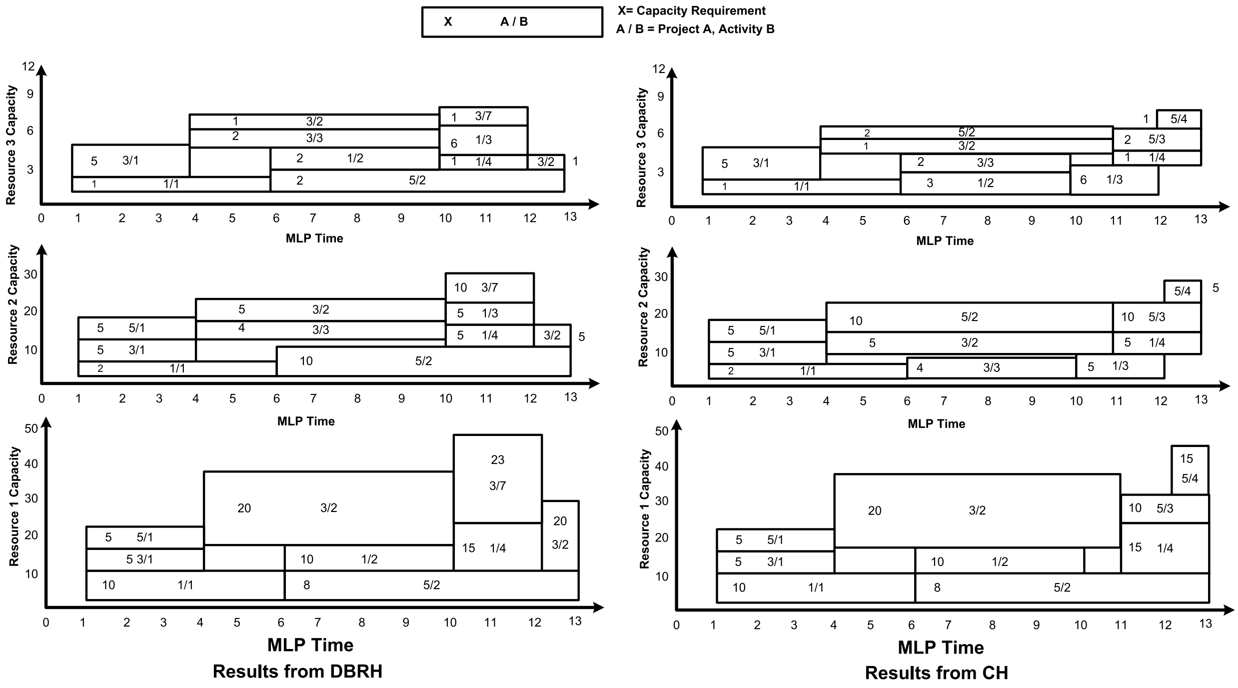


FIGURE 5. Graphical results of multi-level planning of multi-projects at HLP1 and MLP1 obtained from CAH and CH.

in MLP1 obtained from DBRH and Comparing Heuristics (i.e., best result from TS, GA, TS-MTP and GA-MTP) are indicated in Figure. 5.

It can be seen from Figure. 5 that all the three resources are utilized at maximum when the project plan is made from CAH. For instance, the capacity of Resource 1, Resource 2 and Resource 3 are utilized up to the level of 46, 30 and 10 respectively. However, Figure. 5 shows that Resource 1, Resource 2 and Resource 3 are utilized up to the level of 48, 25 and 10 when the project plan is made from comparing heuristics (CH).

B. EXPERIMENTS BASED ON BENCHMARK INSTANCES

1) INPUT DATA FOR MULTI-LEVEL PLANNING PROBLEM INSTANCES FOR MULTI-PROJECT

The standard benchmark projects are used in this section to make different problem instances. Each problem instance is composed of multiple projects and each project data is taken from the standard benchmark single project instances of J30, J60, J90 and J120 given in Kolisch *et al.*, [70]. The standard project data do not have all the required information of the current research problems. The due date of projects are taken from the total chain length of the single projects. Different-problems are created based on J30, J60, J90, J120 benchmark instances and combination of these instances to create the multi-project multi-level planning problems. In these problem instances, the total length of project activities is taken as sum of process time of all activities of the project. The problem instances involves different values of HLP, MLP and duration of each MLP which are taken from the range of (2, 20), (2, 5) and (5, 10) respectively. The number of projects are taken between the range of (4, 10) for each problem instance. Moreover, the projects are taken from the standard problems of single projects based on benchmark projects J30, J60, J90, J120 and combinations of project instances based on benchmark projects from J30, J60, J90 and J120. Different problems of the multi-level planning of multi-projects are illustrated in Table 3. The type of benchmark projects which are newly inserted in the HLP in the problems are indicated as N. For instance, for the benchmark project J30, the project instances J30-3 and J30-4 are represented as J30-3N and J30-4N because they have arrival time of greater than zero. The resource availability for different benchmark projects used in the problems are indicated in Table 3. The due dates and the arrival time of projects in the considered problems are also presented in Table 3. It can be seen from Table 3 that the problems created here involves all kind of benchmark projects in each problem instance.

2) COMPARISON OF RESULTS

The performance of the proposed DBRH is tested based on the problems instances created with the standard benchmark project data. The proposed DBRH is tested with the multi-project multi-level planning results obtained from TS, GA, TS-MTP and GA-MTP, i.e., CH.

50 best results of each problem obtained from TS, GA, TS-MTP and GA-MTP are combined together to make population of best 200 (i.e., 4 times 50) results. 10 results of each problem from these best 200 results are sorted and compared with the results of the proposed DBRH results for

TABLE 3. Data of problem instances created for multi-level planning of multi-projects based on standard benchmark projects.

Problem Instances

Benchmark	**Problem**	**No of HLP**	**No of MLP in HLP**	**Duration of each MLP**	**No of Projects**	**Type of Benchmark Projects**
J30	1	20	2	5	4	J30-1, J30-2, J30-3N, J30-4N
	2	16	2	5	4	J30-5, J30-6, J30-7, J30-8
	3	7	3	10	6	J30-1, J30-2, J30-3N, J30-4N, J30-5, J30-6
	4	7	3	10	7	J30-1, J30-2, J30-3N, J30-4N, J30-5, J30-6, J30-7
	5	7	3	10	8	J30-1, J30-3N, J30-4N, J30-5, J30-7, J30-8, J30-9, J30-10
	6	19	2	5	4	J30-8, J30-9, J30-7, J30-4N
	7	20	2	5	6	J30-1, J30-2, J30-5, J30-8, J30-9, J30-10
J60	8	13	3	10	10	J60-1, J60-2, J60-5, J60-7, J60-8, J60-9, J60-10, J60-11N, J60-12N, J60-15N
	9	13	3	10	10	J60-2, J60-3, J60-4, J60-6, J60-7, J60-9, J60-11N, J60-13N, J60-14N, J60-15N
	10	16	3	10	15	J60-1, J60-2, J60-3, J60-4, J60-5, J60-6, J60-7, J60-8, J60-9, J60-10, J60-11N, J60-12N, J60-13N, J60-14N, J60-15N
J90	11	34	2	5	6	J90-1, J90-2, J90-3, J90-4, J90-5N, J90-6N
J120	12	40	2	5	4	J120-1, J120-2, J120-3, J120-4N
Mix of J30, J60, J60 and J120	13	14	3	10	10	J30-2, J30-7, J30-10, J60-5, J60-6, J60-11N, J90-4, J90-5N, J120-2
	14	37	2	5	6	J30-5, J30-8, J60-4, J60-7, J60-13N, J120-1
	15	16	3	10	15	J30-2, J30-3N, J30-6, J30-8, J30-9, J30-10, J60-1, J60-2, J60-6, J60-14N, J90-4, J90-5, J90-6N, J120-3, J120-4N
	16	37	2	5	6	J30-1, J30-2, J60-5, J60-14N, J90-5N, J120-4N
	17	19	2	10	7	J30-5, J30-8, J60-12N, J60-13N, J60-15N, J90-3, J90-6N
	18	14	3	10	6	J60-8, J60-12N, J90-3, J90-60N, J120-2, J120-3
	19	19	2	10	7	J30-6, J60-1, J60-5, J60-8, J90-1, J90-2, J90-5N

Resource availability for different benchmark projects in problems

Benchmark Project Instance	**Problem**	**For all problems Available capacities of resources**			
		1	**2**	**3**	**4**
		Capacities			
J30	1 to 7	17	14	13	19
J60	8 to 10	37	21	20	28
J90	11	37	21	20	28
J120	12	13	17	22	19
Mix of J30, J60, J90, J120	13	23	28	24	19
	14	13	17	22	19
	15	23	27	32	29
	16	23	27	23	19
	17	13	17	22	19
	18	23	21	16	25
	19	21	17	22	13

Due dates and arrival time of different benchmark projects in problems

Projects based on J30

	J30-1	J30-2	J30-3N	J30-4N	J30-5	J30-6	J30-7	J308	J309	J30-10
Due Dates	195	160	141	184	119	123	157	157	160	149
Arrival Time	0	0	10	20	0	0	0	0	0	0

Projects based on J60

Project	J60-1	J60-2	J60-3	J60-4	J60-5	J60-6	J60-7	J60-8	J60-9	J60-10	J60-11N
Due Dates	329	344	316	324	308	296	341	363	342	354	332
Arrival Time	0	0	0	0	0	0	0	0	0	0	10

Projects based on J60

Project	J60-12N	J60-13N	J60-14N	J60-15N
Due Dates	362	333	323	362
Arrival Time	20	25	15	13

TABLE 3. *(Continued.)* Data of problem instances created for multi-level planning of multi-projects based on standard benchmark projects.

Projects based on J90						
Project	J90-1	J90-2	J90-3	J90-4	J90-5N	J90-6N
Due Dates	338	289	309	301	303	319
Arrival Time	0	0	0	0	30	20
Projects based on J120						
Project	J120-1	J120-2	J120-3	J120-4N		
Due Dates	366	365	395	361		
Arrival Time	0	0	0	30		

each considered problem. Percentage average deviation in the tardiness value of projects is computed using Equation (17) and percentage difference (PD) using Equation (18) are used to compare the results of tardiness obtained from DBRH with CH heuristics. Table 4 shows the tardiness results of the proposed DBRH. Moreover, the average of the best results obtained from the CH are also indicated in Table 4 and represented as ADCH. The percentage of the tardiness value of ADCH with DBRH are also presented in the Table 4. In addition, overall results of the value of percentage average difference of the tardiness of CH with the tardiness value obtained from DBRH are also presented in Table 4 for each problem. It can be seen from Table 4 that the tardiness value of the multi-level plan of multi-projects based on DBRH is smaller as compared to the tardiness value of multiple projects obtained from the schedule made by CH heuristics. The negative values of the tardiness in Table 4 indicates that the projects are not late and they are completed earlier than their corresponding due dates. PAD values are significantly larger for some problems indicated in Table 4 which shows that the tardiness value of the multi-projects is smaller than the tardiness value of the multiple projects which are obtained from CH heuristics

C. EXPERIMENTS BASED ON CASE PROBLEMS

The proposed DBRH is applied to solve two Case Company problems of multi-level planning of multiple projects, i.e., Case Problem A and Case Problem B. The basic detail of the activities of the Case Problem A and B are: [A1: Cylinder block], [A2: Timing gear box], [A3: Flywheel shell], [A4: Crank shaft], [A5: Cylinder cover], [A6: Valve device], [A7: Oil pump], [A8: Oil filter], [A9: Oil cooler], [A10: Oil sump], [A11: Thermostat], [A12: Cooling fan], [A13: Intake & exhaust pipe], [A14: Turbocharger & oil pipe], [A15: Fuel system], [A16: Fuel filter], [A17: Generator unit], [A18: Starter], [A19: Overhaul sealing package – Top], [A20: Overhaul sealing package component lower part], [B1: Main pump], [B2: Regulator], [B3: Gear pump], [B4: Rotary motor], [B5: Rotary deceleration gear], [B6: Walking deceleration gear], [B7: Walking motor], [B8: Control valve], [B9: Pedal valve], [B10: Remote control valve], [B11: Pilot valve], [B12: Solenoid valve], [B13: Crusher valve], [B14: Boom cylinder], [B15: Arm cylinder], [B16: Bucket Cylinder], [B17: Arm cylinder - lock valve], [B18: Bucket cylinder - lock valve].

TABLE 4. Comparison of results of DBRH with the comparing heuristic (CH) for each problem.

Problem Type	Tardiness value		PD	Average PAD of Tardiness
	DBRH	ADCH		
1	-384	-383.7	0.08	0.08
2	-291	-231	26	20.6
3	-485	-383.2	26.5	21
4	-553	-499.6	10.7	9.7
5	-616	-544.5	13.13	11.6
6	-337	-328.3	2.65	2.6
7	-552	-537	2.8	2.7
8	-548	-423	22.72	22.72
9	-233	-26.4	88.6	88.6
10	274	1086	296.5	296.5
11	-795	-617	22.4	22.4
12	-394	-364	7.4	7.4
13	-182	-174	19	19
14	-593	-573	3.4	3.4
15	-682	711	204	204.3
16	-425	-432.6	1.8	1.8
17	-503	-493	15.7	15.7
18	-725	-665.3	8.23	8.23
19	-519	-135.3	74	74

1) CASE COMPANY PROBLEM A AND PROBLEM B

The Case Company problem A and problem B has Engine section and a Pump section which remanufacture different subsections of the engine. There are four different projects in problem A and five projects in problem B. The detail of precedence diagram of problem A and B are indicated in Table 5.

2) COMPARISON OF RESULTS

The Case Company problems, A and B, of multi-level planning of multiple projects are solved using proposed DBRH and other comparing heuristics. The tardiness values obtained from TS, GA, TSMTP, GAMTP and CAH are 806, 809, 815, 823 and 796 respectively for case company problem and tardiness values obtained from TS, GA, TSMTP, GAMTP and DBRH are 394, 394, 396, 403 and 388 respectively for case company problem B. The percentage decrease in tardiness of CAH as compared to TS, GA, TSMTP and GAMTP are 1.2, 1.6, 2.4, and 3.4 respectively for case company

TABLE 5. Detail of projects in Multi-level planning of multiple projects in Case Company problem A and Case Problem B.

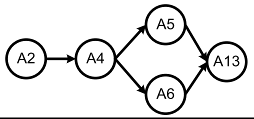
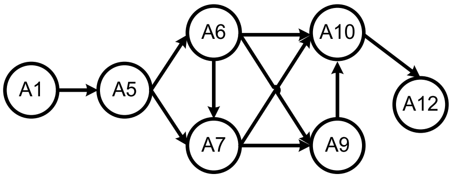
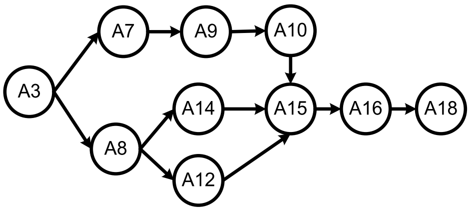
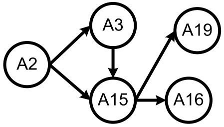
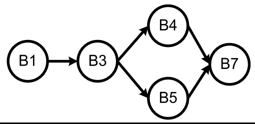
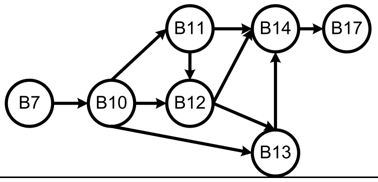
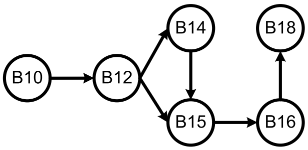
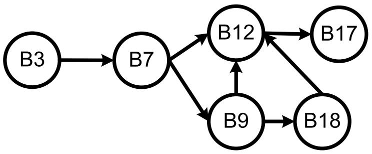
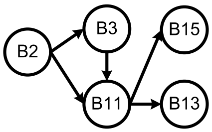
Case Company Problem A							
Projects	**Activity**	**Capacity Requirement of Resource**			**Shipping Buffer**	**Processing Time**	**Arrival time**
		R1	**R2**	**R3**			
Project 1  	A2	10	10	1	1	40	0
	A4	10	10	1	2	10	3
	A5	5	14	0	1	10	1
	A6	20	10	10	1	30	4
	A13	15	15	2	1	20	10
Project 2  	A1	10	5	1	1	20	0
	A5	12	18	0	2	40	14
	A6	15	24	0	1	150	10
	A7	5	20	0	2	150	10
	A9	25	5	0	3	10	12
	A10	5	45	5	4	10	30
	A12	0	10	5	5	20	30
Project 3  	A3	5	5	0	1	20	0
	A7	8	10	2	1	60	8
	A8	10	10	2	1	50	8
	A9	15	5	1	1	40	30
	A10	4	12	3	1	10	5
	A12	7	12	0	0	12	0
	A14	23	20	1	10	10	35
	A15	10	5	0	1	10	2
	A16	5	3	0	1	30	2
	A18	30	2	1	4	12	2
Project 4  	A1	5	10	1	2	15	0
	A3	5	10	1	3	20	14
	A15	5	10	1	3	11	30
	A16	5	10	1	4	10	50
	A19	5	10	1	1	16	20
Case Company Problem B							
	B1	8	9	1	1	40	0
	B3	11	12	1	2	10	3
	B4	6	12	0	1	10	1
Project 1  	B5	18	9	10	1	30	4
	B7	13	16	2	1	20	10
Project 2  	B7	12	5	1	1	20	0
	B10	10	18	0	2	40	14
	B11	17	14	0	1	50	10
	B12	7	21	0	2	50	10
	B13	15	5	0	3	10	12
	B14	8	35	5	4	10	30
	B17	5	10	5	5	20	30
Project 3  	B10	8	2	1	0	3	1
	B12	7	3	1	1	4	0
	B14	3	2	1	1	2	2
	B15	6	2	2	0	3	1
	B16	2	1	1	1	4	0
	B18	5	1	1	1	2	2

TABLE 5. ***(Continued.)*** **Detail of projects in Multi-level planning of multiple projects in Case Company problem A and Case Problem B.**

Project 4 	B3	6	3	0	0	2	1
	B7	5	2	2	0	1	1
	B9	3	4	1	1	3	0
	B12	10	5	1	0	2	3
	B17	0	3	1	1	3	0
	B18	7	7	0	0	2	3
Project 5 	B2	6	8	1	2	15	0
	B3	6	9	1	3	20	14
	B11	6	12	1	3	11	30
	B13	5	12	1	4	10	50
	B15	5	15	1	1	16	20

problem A. Moreover, the percentage decrease in tardiness of DBRH as compared to TS, GA, TSMTP and GAMTP are 1.55, 1.55, 2.1 and 3.9 respectively for case company problem B. These results indicate that the multi-level plan of the multi-projects based on the Case Company Problem A and Problem B, obtained from proposed DBRH is better in quality as compared to the other heuristic methods.

V. CONCLUSION

Current research studied RCMPSP in rolling horizon and integrated HLP and MLP to make efficient schedule of project activities. A drum buffer rope based heuristic for multi-level rolling horizon planning of multi-projects is designed to make DBR based finite capacity plan on MLP to consider the shifting CCSR in each planning horizon and schedule the activities to maximize the utilization of CCDR on the critical chain of the multi-projects. DBRH is proposed to schedule the critical activities of multi-projects on sharing resources to minimize the tardiness of the multi-projects in each planning horizon. In addition, next following relation and next following chain is introduced in the proposed DBRH heuristic. The proposed DBRH creates near optimal results in most of the considered problem instances as compared to the other methods. Moreover, after each planning horizon, the project activities are updated and push and pull strategies are also incorporated to maximize the utilization of critical constraint resources in each planning horizon.

The performance of the proposed DBRH is measured with the performance of the famous algorithms on three different kind of multi-project problems based on simple project data, benchmark project data and Case Company projects data. The simple problems consisting of multiple projects are made in the current study and used for comparison of the DBRH algorithm. In addition, standard benchmark projects taken from literature are used to create set of problems instances of the multi-projects and used for comparison. Moreover, Case Company data of multiple projects is created and used for analysis and comparison of performance of the proposed DBRH. The schedule of multi-project activities obtained from DBRH are compared with the schedules obtained from famous algorithms including standard genetic algorithm (GA), standard simulated annealing (SA), GA with priority of maximum tardiness project (GA-MAT) and SA with maximum tardiness project (SA-MTA) Experimental results indicate that the proposed DBRH gives significantly better results of multi-level planning of multiple projects in rolling horizon and gives efficient integrated multi-level plan of projects with maximum utilization of the constraint resource in each MLP.

In the current research on multi-level planning of resource constraint multiple projects, the duration of activities is considered as known and constant but in real environment, the activity durations of the projects may vary due to uncertainties in the real environment. Therefore, in future multi project planning and scheduling research can be extended to include the uncertain duration of activities of the multiple projects. Further, robust planning and scheduling of multi-projects can be studied in future.

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