

Case Study on Repetitive Scheduling Method

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Abstract : Repetitive construction projects represent a large portion of the construction industry. Construction projects that contain several identical or similar units are usually referred to as repetitive projects which include multi-storey buildings, pipelines, highways, and housing developments projects.

Although the conventional critical path method (CPM) has been widely used in scheduling construction projects, it possesses various deficiencies in scheduling repetitive projects. The Repetitive Scheduling Method (RSM) recognizes the additional resource continuity constraint that cannot be shown in a CPM network, and thus provides for continuous resource usage. It incorporates commonly accepted activity precedence concepts from CPM, and can be applied to both vertical and horizontal projects that may contain either discrete or continuous activities.

An RSM schedule is presented graphically as an X-Y plot of a series of production lines, each of which represent a repetitive activity. RSM introduces the controlling sequence of activities as a new concept for the determination of the project duration. This sequence includes activities between control points on successive unit production lines and extends from projects start to project finish. RSM diagrams are easy to prepare and understand, and the unique concepts of control points and controlling sequence are quickly comprehended. Thus, RSM has all the necessary performance characteristics to serve as a convenient and practical tool for scheduling multi-unit projects.

In this thesis, a plan of 5-storeyed building project is considered in order to represent how RSM can help in achieving work continuity. The total project duration can also be reduced by changing the unit-production rates of various activities. The increase in the unit production rate depends on the availability of the resources. The resource availability needs to be checked before the unit production rate of activities is increased. It has been observed that by increasing the unit production rates of certain activities, the total project duration may be increased the unit production rates of certain activities, the total project duration may be increased after the application rates of certain activities, the total project duration may be increased after the application of RSM. In such cases, there is a need to apply necessary work breaks in order to decrease the total project duration.

1. INTRODUCTION

The success of a construction project depends on the method of scheduling adopted and how effectively it is carried out. Poor scheduling can result in completion delays cost overruns. Scheduling of construction projects that have multiple units, wherein activities repeat from one unit another, always represent a major challenge to project managers. Construction contractors often encounter projects that contain several identical or similar units, such as floors in multistory buildings, houses in housing developments, meters in pipelines, or stations in highways. These multi-unit projects are characterized by repeating activities, which in most instances arise from the subdivision of a generalized activity into specific activities associated with particular units.

The Critical Path Method (CPM), a scheduling method, has been used widely in construction because of its simplicity and most scheduling software offers CPM cannot be used in scheduling repetitive construction projects since it is a pure time-based scheduling approach, not a resource-based approach. The CPM algorithm, therefore, is duration-driven. Activities duration here are function of the resources that are required to complete each activity. The CPM formulation, therefore, assumes that resources are in abundance and cannot be used to determine what resources are needed in order to meet a known project deadline duration.

Resource-drive scheduling, on the other hand, is different and is more focused on resources. Its objective is to schedule the activities so that a project deadline is met using predefined resource availability limits. In this thesis, Repetitive Scheduling Method (RSM), which is a resource-driven type is used for the purpose of scheduling of the undertaken construction project.

1.1 Repetitive Construciton Projects

Repetitive construction projects represent a large portion of the construction industry. Construction projects that contain several identical or similar units are usually referred to as repetitive or linear projects. Linearity may be due to the uniform repetition of a set of activities throughout the project, or due to the physical layout of the project.

Activities that repeat from unit to create a very important need for a construction schedule that facilitates the uninterrupted flow of resources from one unit to the next, since it is often this requirement that establishes activity starting times and determines the overall project duration. Hence, uninterrupted resource utilization becomes an extremely important issue. To maintain work continuity, repertitive units must be scheduled in such a way as to enable timely movement of crews from one unit to the next, avoiding crew idle time. Ensuring work continuity, during scheduling, provides for an efficient resource utilization strategy.

Resource required to perform the work on an activity move from one stage to another. The quantity of resources for each activity is carefully selected to achieve the following goals.

1. To maintain a constant production rate for each crew on each activity throughout the project.
2. To maintain continuity of work for each crew from one stage to the other, thus to eliminate idle time for a crew waiting for preceding crews to finish their work.
3. To allow for times buffers between activities on the same stage-for example, a time buffer between a concreting crew and a formwork crew to allow for curing of concrete.

4. To allow for stage buffers between activities on different stages. For example, bricklaying should be two floors lower than the floor being poured to allow concrete to gain strength.
5. To finish the project at the minimum possible cost given a target project duration.

1.2 Construction Planning

Construction planning is a fundamental activity in the management and execution of construction projects. A good construction plan is the basis for developing the budget and the schedule for work. Construction planning is not an activity which is restricted to the period after the award of a contract for construction. It should be an essential activity during the facility design.

Most repetitive construction projects for which formal plans are prepared tend to be defined with large number of activities. When a project consists of numerous activities, it is often advisable to organize the activities in some way to allow communication of plan information to others and to maintain an understanding of the various aspects of the project. While there are many ways that a plan can be organized, one common practice is the use of Work Breakdown Structure(WBS).

WBS is a convenient method for decomposing the project complexity in a rational manner into work packages and elementary activities. These work packages are then coded so that both costs and the schedule can be controlled. A common numerical accounting system is then applied to the activities, so that the coding indicated factors such as the type of material involved or the physical location within the project.

In essence, WBS divides and subdivides a project into different components by area, phase, function, or other considerations. The highest level in WBS consists of a single element, the project. At the next level, there may be only a few elements or items. Naturally, the further one goes down within the WBS, the greater the granularity of decomposition and the amount of detail.

Therefore, WBS is deliverable- oriented decomposition of the project scope until a sufficient level of granularity enables easy definition of all information required to execute and manage detailed tasks.

1.3 Construction Scheduling

A schedule is also a good communication tool, between the managers, owners, investors, and the general public. Once a plan is complete, it has to be communicated to the different levels of supervision and execution within the project. Scheduling is a means of communicating the project strategy and determining the amount of time required to carry it out. A schedule must be made to make optimal use of time and to ensure the activities are completed in time so that no sacrifices are made in the quality of the planning in order to meet deadlines.

The construction schedule is usually based on the WBS and is very meticulous. It usually includes detailed plans, such as engineering schedules, construction sequencing, quality assurance activities, as well as procurement plans.

The development of an effective and realistic schedule requires the following steps.

1. The construction activities and tasks must be sequenced in the most logical and efficient order.
2. A duration must be assigned to each and every single activity and task within the schedule, and
3. Adjustments must be made as deemed necessary to ensure the schedule matches the planned strategy and time frame required to complete the job.

1.4 Problem Statement

The scheduling problem posed by multi-unit projects with repeating activities is akin to the minimization of the project duration subject to resource continuity constraints as well as technical precedence constraints.

The critical path method (CPM) is the most widely used and accepted planning and scheduling method for traditional (non-repetitive) projects. However, CPM does not suit the planning and scheduling needs of repetitive projects.

1.5 Limitations of Network Scheduling Methods

CPM-based techniques have been criticized widely for their inability repetitive projects. The first problem is the sheer size of the network. In a repetitive project of 'n' units, the network prepared for one unit has to be repeated 'n' times and linked to the others which results in a huge network that is difficult to manage. This may cause difficulties in communication among the members of the construction management team.

The second problem is that the CPM algorithm is designed for optimizing project duration rather than dealing adequately with the special resource constraints of repetitive projects. The CPM algorithm has no capability that would ensure a smooth procession of crews from unit to unit with no conflict and no idle time for workers and equipment. This leads to hiring and procurement problems in the flow of labor and material during construction.

Network techniques emphasize on minimizing the total project duration and thus make the unrealistic assumption that resources are unlimited and centrally controlled. Therefore, contractors avoid using these network schedules in highly repetitive projects such as high-rise buildings since these projects are highly resource constrained in addition to being time constrained.

Another disadvantage of network scheduling techniques is that for complex projects, a network schedule tends to become extremely complex and detailed. For example, if a high-rise building with 25 typical floors is to be considered and if the work of each floor is broken down into 22 activities, the project network would consist of 550 activities, which complicates the understanding of the schedule and control process.

1.6 CPM Multi-unit Scheduling

Multi-unit projects can be scheduled using commonly accepted CPM techniques, but continuous utilization of resources across repeating units cannot be assured when these CPM networks are used. This shortcoming is best illustrated by an example.

Figure 1.1 is a CPM network prepared for a project consisting of three repeating units of work. The solid lines linking the activities within each unit and linking similar activities from unit to unit represent the technical precedence constraints in the network; for example, Activities B1, C1, and A2 cannot begin until the crew of carpenters from Activity A1 is available.

Note that Units 1 and 3 each have five activities, A through E, but Unit 2 does not contain a B activity. Unit 2 also differs in that the individual activity durations are not the same as in Unit 1 and 3. These differences reflect the various amounts of work needed to complete the activities of the unit.

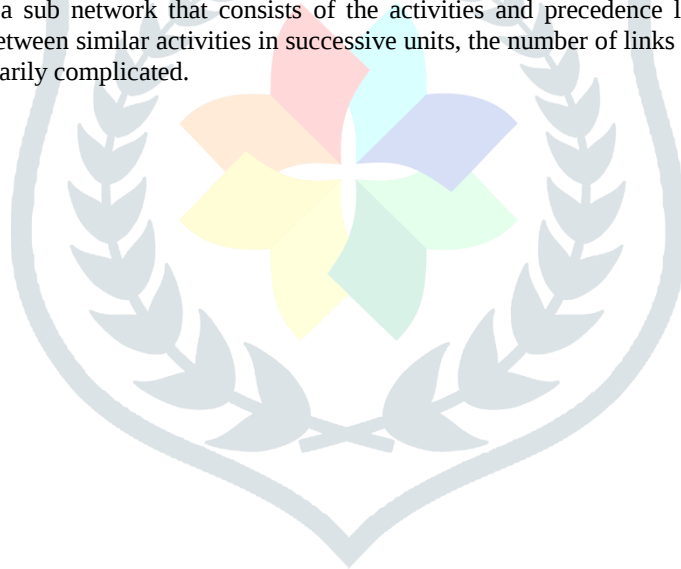
The solution of the network in Figure 1.1 results in a project duration of 18 days and a critical path that includes Activities A1, C1, C2, D2, D3, and E3. Typically, each unit in a repetitive network contains the same activities having the same durations, and the critical path passes through the network of activities in the first unit until an activity with a long duration is found. The path then passes through similar activities in successive units until the last unit in the sequence is reached, and continues through the last unit network until the final activity is completed. Had all three units in Figure 1.1 been alike, the path would have included Activities A1, C1, C2, C3, D3, and E3. The shift in the path to include Activity D2 and not C3 as expected is caused by the activity differences in Unit 2.

The links in this CPM network ensure that both technical precedence and resource availability requirements are met. However, resource continuity constraints cannot be represented directly in CPM network, so the uninterrupted utilization of resources from unit to unit cannot be assured. The schedule shown in Figure 1.1 does provide for the continuous usage of the resource used by the C activities. Activity C1 begins on Day 3 and ends on Day 7, Activity C2 begins on Day 7 and ends on Day 10, and Activity C3 begins on Day 10 and ends on Day 14, so the use of the resource is uninterrupted from Day 3 to Day 14.

For the D activities, the scheduled times do not provide continuous resource utilization. Activity D1 is scheduled to finish on Day 9, but the start of Activity D2 is not scheduled to begin until one day later (i.e., on Day 10). Therefore, there is a one day gap in the utilization of the resource needed for the D activities. Similarly, resource continuity is provided by the schedule of the A activities, but is not achieved for the B and E activities.

When uninterrupted utilization of resources is needed, activities having breaks in resource continuity can be rescheduled using their float times. For example, the one day Total Float for Activity D1 can be utilized, and D1 can be rescheduled to start on Day 8 and end on Day 10. In large projects with repeating activities, a complete activity-by activity analysis and correction of the CPM network is required to ensure resource continuity, a process that is cumbersome and fraught with the possibility of error.

It may also be concluded from Figure 1.1 that CPM network for projects with repeating units of work have a ladder-like appearance where each rung is a sub network that consists of the activities and precedence links for one unit. Because CPM diagrams show all the linkages between similar activities in successive units, the number of links and nodes will likely be large and the network will appear unnecessarily complicated.



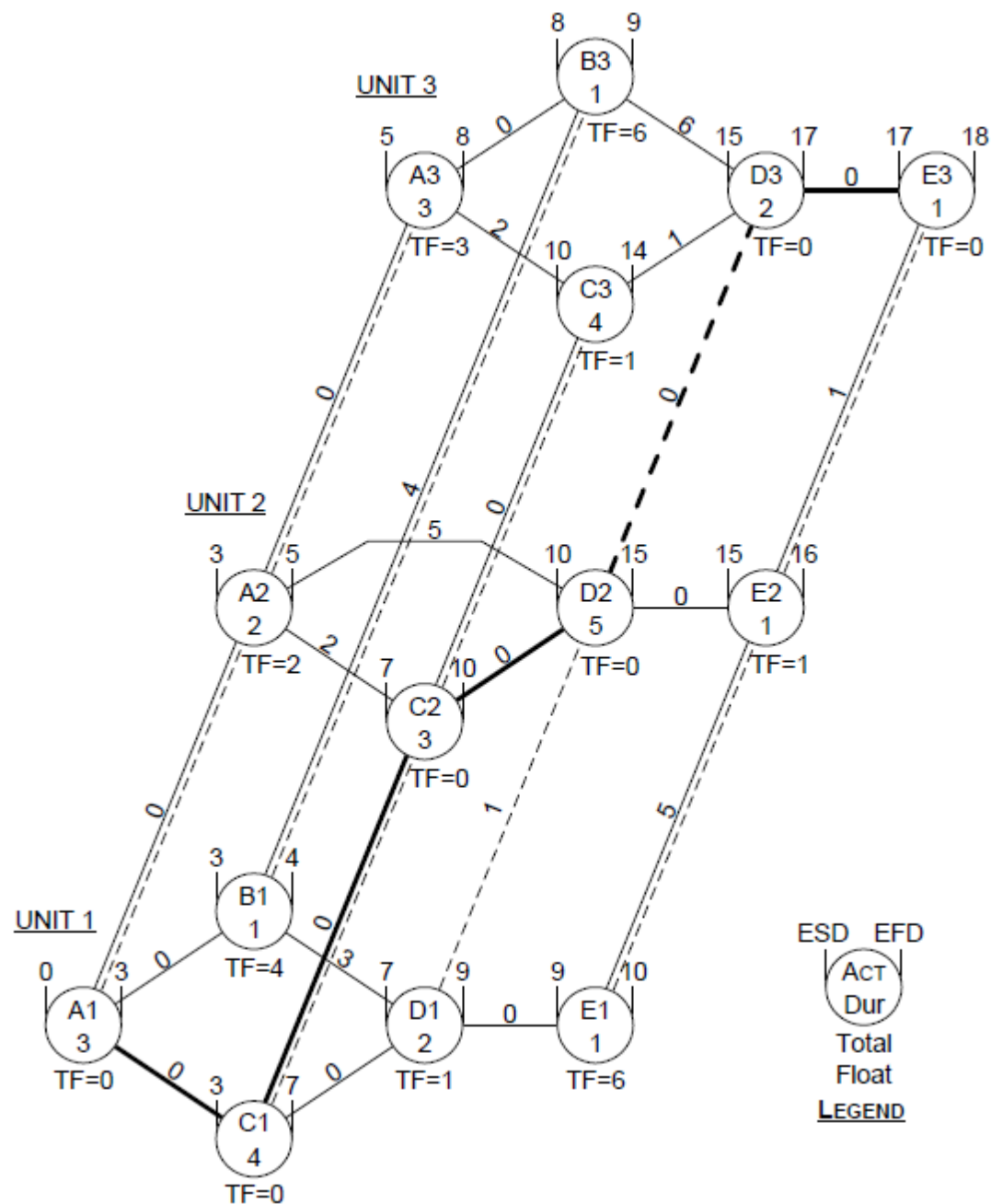


FIGURE 1.1 CPM NETWORK FOR THREE REPETITIVE UNITS

1.6 CPM Vs RSM

The differences between Critical Path Method (CPM) and Repetitive Scheduling Method (RSM) can be summarized as follows:

	Critical Path Method (CPM)		Repetitive Scheduling Method (RSM)
1.	CPM is a duration-based scheduling technique.	1.	RSM is a resource-based scheduling technique.
2.	This technique emphasize on minimizing the total project duration and thus make an unrealistic assumption that the resources are unlimited.	2.	The objective of this technique is not minimization of the project duration but achieving work continuity which leads to the minimizing the overall project cost.
3.	CPM is shown by node and arrow diagram where nodes represent the activities and activity information while arrows represent the inter-relationships between activities.	3.	RSM is presented graphically as an X-Y plot of unit production lines where one axis of plot represents time and the repetitive units on the other axis.
4.	In CPM, chain or sequence of activities that establishes minimum project duration is called critical path.	4.	In RSM, chain or sequence of activities that establishes minimum project duration is called controlling sequence.

5.	CPM calculations satisfy only logical dependencies between network activities.	5.	In RSM, resource continuity should be considered in addition to the logical dependencies.
6.	In CPM, the total resource idle time is not reduced.	6.	In RSM, the total resource idle time is reduced.
7.	This method does not ensure continuity in resource utilization.	7.	This method ensures continuity in resource utilization.
8.	This technique is used in simple building projects and not in repetitive projects.	8.	This technique is used in repetitive projects like high-rise buildings, tunnels, highways.

2. LITERATURE REVIEW

2.1 INTRODUCTION

This chapter reviews the available literature that is related to repetitive construction projects from several perspectives. Many scheduling techniques have been developed for planning and scheduling of repetitive projects. These techniques include:

1. Critical Path Method (CPM)
2. Program Evaluation and Review Technique (PERT)
3. Line-of-Balance (LOB)
4. Vertical Production Method (VPM)
5. Linear Scheduling Method (LSM)
6. Horizontal and Vertical Logic Scheduling method (HVLS)
7. Linear Programming (LP)
8. Repetitive Project Model (RPM)

2.2. EXISTING TECHNIQUES

The following discussion concentrates on the advantages and disadvantages of the existing techniques and their underlying concepts. Various aspects of repetitive project scheduling and their ultimate objectives are assessed to verify their practical usages and their realistic representatives of construction projects.

2.2.1 Critical Path Method (CPM)

The Critical Path Method (CPM) was developed in the 1950s by James Kelly and Morgan Walker. The method offers an easy calculation to derive a project schedule and to assess the criticality of activities using its proposed concepts of floats and the critical path, focusing on time. Activities and their interrelationships are depicted in a network by nodes and arrows. Nodes represent the activities and activity information such as title, duration, etc. Arrows represent the interrelationships (precedence constraints) between activities and the lead time between them. After the network is constructed and the activity durations are given, the calculation of critical path, critical activities, and floats can be performed straightforwardly.

The derived information informs project managers of the criticality of activities, which allows them to plan in advance how to schedule the activities and manage the project effectively, based on the current schedule. On the other hand, the managers may decide to alter the original schedule to suit the project deadline, the company resources, and so forth.

Most scheduling software (Microsoft Project, Primavera, etc.) offers automation of CPM calculation and network drawing, within seconds after inputting data. These programs facilitate schedulers in altering and uploading the schedule purposely for planning and controlling. Accordingly, CPM has been widely used in the construction industry.

However, CPM has been criticized for its incapability of taking resource consideration into account in its calculations. This usually leads to an unfeasible schedule due to the unawareness of resource constraints such as resource availability constraints.

From the perspective of repetitive project scheduling, CPM is incapable of capturing the realistic and stochastic nature of repetitive projects (Reda 1990; Harris and Ioannou).

The reasons for such incapability are:

1) CPM does not take resources into account in calculating schedules. It is designed primarily for scheduling and monitoring activity and project duration; CPM is a pure time-based schedule technique. CPM cannot ensure the continuous resource utilization of a crew from unit to unit. Therefore, it cannot maximize efficiency in resource utilization.

2) CPM calculation does not include nor is it concerned with the imbalanced production rate of resources resulting in inefficient resource utilization.

3) CPM is not applicable to non-deterministic activity duration. It is important to recognize that CPM, as a deterministic scheduling method, would schedule projects only to the level of reliability of the input values of the duration of activities. For reliable representation, the productivity data must be expressed in some probabilistic measure.

4) CPM cannot eliminate idle time, since it schedules activities based on their earliest start dates, (Reda 1990, Yang 2002). If a predecessor has a lower production rate than its successor, the successor must wait until the predecessor completes, which results in idle time.

5) CPM and its graphical presentation are considered ineffective when applied to repetitive projects having a large number of units. Its calculation becomes tedious and labor intensive (Yang 2002). For example, a repetitive project consisting of 7 activities for 1000 units will require 7000 nodes to represent the network. A network of this size is confusing and unmanageable (Reda 1990; Yang 2002).

To alleviate the mentioned deficiencies of CPM, the integrations of CPM and other techniques such as Line-Of-Balance (LOB) have been developed during the last couple of decades. Nevertheless, they still cannot handle the stochastic nature in the repetitive projects.

2.2.2 Project Evaluation and Review Technique (PERT)

The Project Evaluation and Review Technique (PERT) was introduced to the construction industry in the 1950s. It is a probabilistic scheduling technique using three point estimates of activity durations to determine an estimated project duration. The difference between CPM and PERT is that PERT is capable of scheduling non-deterministic activity durations while CPM cannot.

However, PERT has not been widely used in the construction industry compared to CPM as it requires more data of activity durations, which is often difficult to obtain and justify. Moreover, PERT requires intensive computation compared to CPM. Since the technology of personal computers has been improved in the last couple to CPM. Since the technology of personal computers has been improved in the last couple of decades, the improved technology causes simulation method to supersede PERT. From a repetitive project perspective, PERT and CPM have the same limitations due to their underlying time-based scheduling calculation and their graphical presentation in precedence networks (Yang 2002).

2.2.3 Line-Of-Balance (LOB)

The Line-Of-Balance method (LOB) was developed at the Goodyear Company by George E. Fouch in the early 1940's for the purpose of managing and controlling production processes in industrial manufacturing where tasks are repetitive. Then, LOB was applied in the Navy (Miller 1963). LOB's main objective is to balance the size of labors and machines based on their production rates so that their resources are employed at full capacities. The major benefit of LOB to construction scheduling is that it conveys important production rate and duration information in a graphical format.

LOB shows progress of activities against time in graphical presentation. The accumulated work completed is plotted with work progress on the Y-axis and time on the X-axis. The line representing completed work is termed the "Production Line". It is evident that LOB offers a better visual presentation than the precedence network, especially for repetitive projects, because the comparisons between activities and between units can be easily perceived in the diagram.

The easily interpreted graphics format enhances the viewers understanding of the project and also individual activities. It allows the viewers to detect a potential bottlenecks by simply observing the production lines.

LOB allows schedulers to observe and adjust the production rate of activities in a production diagram to maximize resource utilization. This process of adjusting production rate is known as "balancing production rates." LOB provides a means of selecting crew size in order to minimize inefficiency and waste in resource utilization. To balance unit production rates, activities are assigned to work at the minimum unit production rate among activities. For example, Activities A, B, and C have unit production rates of A, B, and C should be set at a rate of 1 unit/day. Thus, to balance these activities, production rates of A, B, and C should be set at a rate of 1 unit/day. Thus, to balance these activities, production rates of A, B, and C should be set a rate of 1 unit/day. If the scheduler desires to expedite the project furthermore, more resources could be assigned to Activities A and B so that they progress as fast as Activity C. For this example, additional resources must be assigned to Activities A and B to speed up their unit production rates to 3 unit/day.

The application and graphical presentation (production diagram) of LOB facilitate schedulers in construction a schedule that satisfies precedence constraints, resource availability constraints, and resource continuity constraints. The concepts of continuous resource utilization and balancing production rates benefit repetitive projects in several ways. First, the former maximized the efficiency of resource utilization by eliminating idle time. Since resources are scheduled to work continuously, the project will benefit from the learning phenomenon especially in labor-intensive activities.

Secondly, balancing production rates keeps all activities working at the same pace and possibly reduces project duration. According to the advantages of LOB, many researchers have adopted and adapted these concepts in order to optimize project duration and project cost. The tradeoff between project duration and cost can be analyzed by various techniques, such as integer programming, linear programming, and dynamic programming.

Mendes and Heineck, (1998) considered the Line of Balance LOB technique, which was developed in the early 40's, and adapted for using on construction industry in the 70's, as a production scheduling and control technique which tries to surpass the CPM difficulties for repetitive projects scheduling. The main concept on the line of balance is the work continuity of the labor teams over the construction units. The labor teams work with "Rhythmic Production", and no wastes are willingly planned or introduced into the schedule. In order to find the optimum use of resources, crews and equipment are designed to yield the same production rate "Rhythmic Production", in terms of construction units. If activities are planned to be built in this way, all activities could become critical. Thus, an "all activities critical" planning might not be applicable for the whole project.

However, the fundamental principal of LOB has several drawbacks, which need to be attuned and improved in order to suit the nature of construction projects. The limitations of LOB and solutions are described below. One of the unrealistic assumptions of LOB is the assumption of activities' constant production rates of activities are constant (Yang 2002). This assumption implies that

- 1) work amounts in each unit are identical
- 2) productivity of resources in each activity is a constant.

For repetitive construction projects, the amount of works in each unit could be different from unit to unit; it is rarely the same. For example, high-rise buildings consisting of several floors usually have various types of interior finishing on different floors. Another example is highway projects. Excavation at different locations is likely to result in diverse amounts of soil, according to an existing ground profile.

Senior (1993) stated that the inability to incorporate varying amount of works in repetitive sub-activities is another limitation of LOB. Repetitive projects usually consist of non-typical activities and non-repetitive activities. Non-typical activities are activities having different work amounts in each unit. Non-repetitive activities are activities existing only in a few units.

In addition, Halpin and Woodhead (1976) stated that construction operations are stochastic by nature; thus, assuming production rates are constant may be erroneous. This unrealistic assumption of constant production rates limits the application of

LOB to certain degree of realism and complexity (Yang 2002). To alleviate the deficiency in LOB, the calculation of LOB must be modified in order for it to be applicable to repetitive projects with non-typical repetitive activities (difference in work amounts) and non-repetitive activities (work not existing in all units).

From a resource utilization perspective, Yang (2002) pointed out the assumption of constant production rates limits LOB in two ways. First, each activity must be performed by the same crew. At a project level, this may not be a serious issue, but at a company level this assumption eliminates the possibility of allocating resources among projects. Second, the hard-logic precedence constraints used in LOB may unnecessarily restrain repetitive activities to work in the same sequence from one unit to another.

Carr and Mayer (1974) suggested that the working sequence of units within activities, not constrained by resource or technological constraints, should be “a matter of choice rather than dependency”. In other words, the dependency between activities should be modeled by “soft logic” constraints when possible.

Ironically, the benefit of maintaining continuous resource utilization in LOB has also been argued to be a disadvantage of LOB because of the inability to relax the continuity constraints. In a time-cost optimization problem, the tradeoff between continuity and interruption in work must be analyzed and balanced to achieve the minimum project cost. Without the ability to relax the resource continuity constraints, the project duration may be excessively delayed; as a result, the increased indirect cost (from the delay) exceeds the savings in the direct cost (from eliminated idle time).

Since LOB schedules activities in such a way that activities must work continuously, the benefit from allowing the interruption cannot be obtained. It is a fact that idle time in resource utilization is considered waste at the activity level. However, with no consideration of project cost, this may always be valid at the project level (Reda 1990; Lutz 1990). Focusing on continuous resource utilization and project duration, a schedule derived from LOB may increase project cost, although project duration is reduced. This is a time-cost tradeoff problem. While maintaining 100 percent work continuity results in much greater project duration and consequently indirect cost, allowing interruption (relaxing continuity constraints) could reduce the project duration and indirect cost significantly with a negligible penalty costs from allowing idle time.

From a company stand point, dynamically allocating resources among projects may incur idle time or waste at a project level; however, this would provide better resource utilization and cost efficiency at the company level (Lutz 1990). Thus, allowing interruption in resource utilization should also be considered as an option (Yang 2002). Another shortcoming of LOB is that its graphical presentation becomes confusing when many concurrent activities take place in a particular period. It is designed to model simple repetitive works; thus, LOB's graphical presentation is not readily fit to the complexity of construction projects (Kavanagh 1985; Neale and Raju 1988).

An additional concern about LOB in construction was that it has not been used widely because it is not as readily computerized as network methods (Lutz 1990; Yang 2003). However, this has changed because of the great improvement in computation over the last decades. Examples of computerized LOB combining graphical and analytical methods to solve repetitive project scheduling problems are works from Yang (2002).

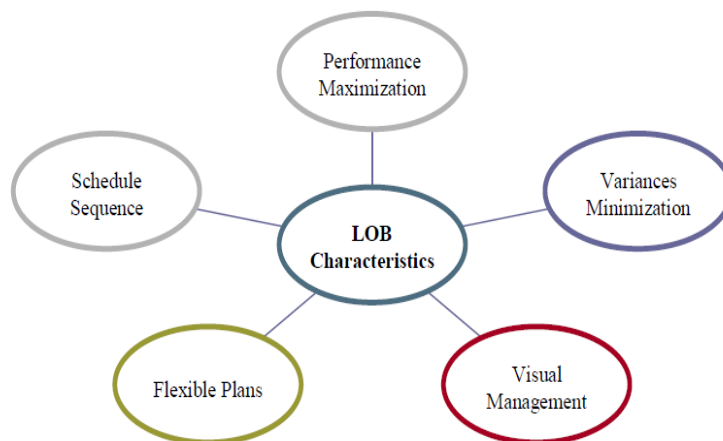


Figure 2.1 LOB Scheduling Characteristics

2.2.4 Vertical Production Method (VPM)

O'Brien (1975) introduced the Vertical Production Method (VPM) which is a graphical method and its main application is in scheduling high-rise buildings by considering each floor as a repetitive unit. He addressed the necessity of integrating between non-repetitive and repetitive works for high-rise buildings. VPM employs a node network to represent non-repetitive activities such as excavation existing only in the first floor of a building. For repetitive activities, cumulative production is plotted on the Y-axis while time is plotted on the X-axis, similar to most graphical approaches. Accordingly, two separate schedule formats are used to present a repetitive project. According to Senior (1993), a drawback of VPM is that it requires planners to manually combine CPM to LOB. Therefore, VPM is not suitable for big scale or complex projects.

2.2.5 Linear Scheduling Method (LSM)

The Linear Scheduling Method (LSM) was first introduced by Johnston (1981). Its graphical presentation, linear scheduling diagram, is very similar to line-of-balance diagram. The main difference between an LOB diagram and an LSM diagram is that an

LOB diagram usually presents a discrete cumulative progress (e.g., floors) while LSM diagram presents continuous cumulative progress (e.g., miles). Moreover, activities in an LOB diagram are presented by horizontal lines from the start to the finish of the activities while activities in an LSM diagram are presented by production lines with the slope of activity unit production rates. However, since many researchers have adopted the concept of LOB but using LSM diagrams (according to Johnston's work) to present activities, LOB diagrams and LSM diagrams are referred and used interchangeably in construction.

Besides the graphical presentations, Johnston noted a difference between LSM and LOB is in their emphasis. While the application of LOB focuses on balancing production lines, LSM concentrates on planning the activities (Johnston 1981). He showed that time-cost optimization can be accomplished by a simple calculation incorporating with the LSM diagram. Comparing to a node network and a bar chart, a LSM diagram provides richer information (such as production rate and production line) allowing schedulers to visualize the process of optimization.

Moreover, Johnston (1981) suggested that seasonal adjustments should be included into LSM diagrams, because holidays and bad weather adversely affect activity productivity. During the course of constructing an LSM diagram, either reduction in production rates or work interruptions must be introduced to the affected activities in order to reflect a realistic schedule.

After the introduction of LOB and LSM, variations between LOB and LSM were developed to improve the means of scheduling repetitive projects.

Ragolia, (1998) proposed the linear scheduling, a pull-driven methodology, as the clearest way to show the construction process on projects that have a repetitive nature. A time-space scheduling or linear schedule is useful because it clearly shows the connections of activities, their duration, and the space where they take place at a given time.

2.2.6 Horizontal and Vertical Logic Scheduling method (HVLS)

Thabet (1992) proposed a method called "Horizontal and Vertical Logic Scheduling method" (HVLS), which combines graphical, knowledge-based, and analytical methods in order to schedule multistory buildings. The HVLS application is considered the very first LOB- computerized extension that provides a full benefit of construction information system. It is user-friendly and database-driven and utilizes information extracted from a 3D CAD model.

In Thabet's thesis, he included space constraints into scheduling in addition to precedence, resource availability, and resource continuity constraints. Thabet suggested that

- 1) Activities in multistory buildings are performed within a limited space and
- 2) Material requires storage area.

Ignoring the requirements of work and storage areas may incur a conflict among different trades, decrease productivity, impact safety, and lengthen project duration (Thabet 1992; Thabet and Beliveau 1994). Effectively incorporating the space and continuity constraints into technical constraints, Thabet grouped technical constraints into 2 categories: horizontal and vertical constraints. The vertical and continuity constraints impose on activities in different units, while the horizontal and space constraints impose on activities in the same unit. During the course of scheduling, these constraints must be satisfied.

The drawbacks of Thabet's work are

- 1) not considering non-typical activities and
- 2) not considering non-repetitive activities (Yang 2002).

His solution can solve only a problem with constant production rates and the same work quantity in all units. In reality, production rates are varied and work quantity among units is unlikely exact the same. According to the drawbacks, his work is limited to simplified problems of repetitive project scheduling.

2.2.7 Linear Programming (LP)

Linear Programming (LP) can be described as a mathematical procedure for minimizing or maximizing a linear function of multiple variables with a defined set of constraints for these variables. LP problems consist of two components:

- 1) an objective function to be maximized or minimized and
- 2) constraints defining linear relationships between variables.

Given linear relationships between variables, a time-cost tradeoff problem or resource allocation problem can be solved effectively by using LP. However, the limitation of LP is the assumption of linear relationships among variables (Lutz 1990). Existing linear programming models often simplify the complexity of repetitive projects.

According to El-Rayes (1997), most methods employing linear programming assume that all activities are typical activities. For example, these methods often assume that durations of interior activities from the first to the last floor are the same. This assumption is not practical. Since duration is influenced by crew productivity, different work amounts, and so on, the durations of sub-activities (for the same repetitive activity) in different units are rarely the same.

Based on the aforementioned, it can be concluded that linear programming does not suit complex situations common in construction.

Perera (1983) used LP to determine the maximum rate of construction. The model consists of three main constraints: limited resource constraints, material constraints, and financial constraints. After all constraints are established, the rate of completion is maximized to derive the optimum number of crews for all activities. Since the objective function is maximizing the rate of completion, it does not provide the optimum project cost which in fact should be considered as the main objective (El-Rayes 1997). Moreover, Perera's model cannot model non-typical activities because it assumes identical duration among units of an activity (El-Rayes 1997). Most importantly, from a resource utilization perspective, Perera's model does not consider the continuity in resource usage (Yang 2002) nor allow work interruption (El-Rayes 1997).

2.2.8 Repetitive Project Model (RPM)

Reda (1990) used LP to optimize the time-cost tradeoff problem for repetitive projects. The proposed model was named the "Repetitive Project Model" (RPM). Compared to other linear programming models, the advantage of Reda's model is that it includes cost as a decision variable in the optimization process (Moselhi and El-Rayes 1993).

The objective of Reda's RPM is minimizing project direct cost for feasible project duration while satisfying the following constraints:

- 1) Maintain a constant production rate for each crew
- 2) Maintain a continuity of work for each crew
- 3) Allow for a time buffer between activities on the same stage
- 4) Allow for a stage buffer between concurrent activities
- 5) Specify feasible project duration

Reda's model guarantees continuity in work flow by using a time buffer between activities, postponing the start date of the succeeding activity. Based on continuity constraints and buffer constraints, work interruption is not allowed; the benefit of allowing interruption is neglected. The lack of considering deliberate interruptions is one of Reda's model drawbacks. The inflexibility in continuous resource utilization and the unrealistic assumption of a constant production rate are the major disadvantages of RPM (Yang 2002).

In addition, the process of formulation in Reda's model could be cumbersome as the number of units increases because the number of constraints depends on the number of repetitive activities. Thus, it is limited by the complexity of establishing the constraints (El-Rayes 1997).

2.3 SUMMARY

Many approaches have been proposed to solve the problems of scheduling repetitive projects. Although the Critical Path Method (CPM) can be applied to repetitive projects, it cannot schedule repetitive projects effectively. Because CPM is designed for optimizing project duration, it does not suit the resource-driven nature of repetitive projects. Moreover, constructing a CPM network for a repetitive project can be tedious and cumbersome when the project consists of many repetitive units. Similarly, the Program Evaluation and Review Technique (PERT) has the same limitations as that of the CPM.

Ever since the Line-Of-Balance technique (LOB) was introduced to the construction industry, it has been influencing many researchers to improve the means of scheduling repetitive construction projects. Many assumptions of LOB are not true with the nature of construction projects. The main conflict is the assumption of constant production rates, which applies only to typical activities.

Past research contributed a number of practical concerns in scheduling repetitive projects. RSM plays an important role in overcoming the drawbacks of the existing methods. RSM has the following advantages over the existing methods :-

- a) RSM maintains work continuity from one stage to another thereby eliminating the resource idle time.
- b) This method can be applied even if the production rates vary from one stage to another for the given activity.
- c) RSM can be applied even for the activities which may not be present at all stages.
- d) RSM can be applied for any kind of precedence relationships (finish to- start, finish-to-finish, start-to-start, and start-to-finish).
- e) RSM allows work interruption if desired. That is, work continuity of crews can be treated as a flexible option.(Yang and Ioannou, 2001).
- f) RSM allows for time buffer between activities on the same stage.
- g) RSM allows for stage buffer between activities on the different stage.

3. METHODOLOGY

The methodology used in this thesis is the use of Repetitive Scheduling Method (RSM) for the planning and scheduling of repetitive construction projects to overcome the limitations of the traditional networking techniques.

The Repetitive Scheduling Method (RSM) recognizes the additional resource continuity constraint that cannot be shown in a CPM network, and thus provides for continuous resource usage. It incorporates commonly accepted activity precedence concepts from CPM, and can be applied to both vertical and horizontal projects that may contain either discrete or continuous activities.

The construction of RSM schedules involves the positioning of successive unit production lines by using the new concept of control points. There is a specific point along each production line that controls the schedule position of its successor production line. This point, called a control point, tends to be located toward the first unit in the sequence of units if the lines diverge, and toward the last unit in the sequence if the lines converge. These control points have significance in the determination of the project duration, and serve as points of rotation for unit production lines whose resource rates are increased or decreased.

3.1 RSM SCHEDULE REPRESENTATION

An RSM schedule is presented graphically as an X-Y plot where one axis represents units, and the other time. For vertical construction projects, the repetitive units are usually discrete entities, such as houses, stores, apartments, or floors in high-rise construction, and work progress is measured in units completed. Hence, the units are typically shown along the Y-axis and time is shown along the X-axis. For horizontal construction projects, such as highways, pipelines, canals, tunnels, and so forth, work progress is measured in units of length and these units are shown along the X-axis to correlate with horizontal and vertical alignment charts, while time is shown along the Y-axis.

The repetitive units of the project must be arranged in some logical sequence along the chosen axis to define their pattern of repetition. This sequence may be accepted as a natural occurrence or may be established to suit some production need. For

example, building floors must naturally be constructed one upon another, stations along a highway may follow in the natural numerical order from project start to project finish, or may be planned to recognize particular site or traffic conditions. [2]

3.2 RSM ACTIVITY LOGIC

In addition to establishing the pattern by which repetitive units follow each other, it is necessary to identify the precedence constraints among the activities in each unit. To do so, a CPM precedence network is prepared for each typical repetitive unit, or if necessary, for each non-typical unit.

The process to establish unit activity logic begins with the creation of a list of all the time consuming activities necessary for the completion of the project. Each activity in the list is given a name and the list is analyzed to determine the proper dependency relationships and to remove redundancies.

An examination of the activity list will most likely show groups of similar activities occurring again and again. For example, it may be observed that activities describing the construction of the first typical floor of a multistory building are repeated for several other succeeding floors. The collection of activities needed for each floor represents the details of a repetitive unit that is identified with that floor. The number of activities in the repetitive unit is not an important matter, because it is determined by the nature of the project. In some instances, the unit may contain only one activity.

Once all activities belonging to each repetitive unit have been identified, a logic diagram is prepared. This diagram can be either in the form of an arrow or a precedence network, but the precedence form is preferred. Each unit network should contain all production and want logic relationships among the activities. Because the main purpose of this diagram is to establish logical relationships among the activities, resource considerations within this unit can be temporarily ignored.

3.2.1 ACTIVITY LOGIC CONSTRAINTS

While the activities within a repetitive unit must be logically related, they also must be logically related from unit to unit according to the logical sequence pattern of the units as previously described. There are two types of constraints that control unit-to-unit logic in RSM diagrams; one is a technical precedence constraint and the other is a resource availability constraint. In the first instance, a particular work activity in the network of one unit must be followed by a similar work activity in the network of a succeeding unit to ensure that the flow of the technical work between the units is maintained. In the second case, the resource assigned to an activity in one unit also must be assigned to the similar activity in the succeeding unit to ensure that the resource required in the first unit is available when needed by the second unit. Note that this does not ensure that the resource between the two units will be used continuously.[2]

3.3 RESOURCE CONSIDERATIONS

RSM assumes that the same resource will be used for like activities in successive repeating units, so each activity's resource must be consistent from unit to unit. For example, if an activity in the first unit requires a crew of carpenters, that activity in each succeeding unit will require the same crew of carpenters.

The resource production rate for an activity, $rprA$, is the amount of work that can be accomplished by the resource in the given time period. In equation form:

$$rprA = Q_{Ai} / T_{Ai}$$

Where $rprA$ is the resource production rate; Q_{Ai} , is the quantity of work done in activity A, in any repeating unit, i ; and T_{Ai} is the time needed to complete the 'A' activity in unit i .

The unit production rate is the number of repetitive units that can be accomplished by a resource during a unit of time. For an activity, A, in any repeating unit, i , the unit production rate, $uprA_i$, can be expressed as:

$$uprA_i = 1 / T_{Ai}$$

Where T_{Ai} is the time needed to complete the unit. The unit production rate is the slope of a production line in an RSM diagram.[13]

4. BASIC RSM CONCEPTS

RSM employs a pull-system approach, where the finish time of the predecessor activity is pulled forward to meet the start date of the successor in order to achieve work continuity and uninterrupted resource utilization, in contrast with the CPM push system, where the start of every activity is pushed in time to maintain the precedence relationships with its predecessors. The objective in RSM is not minimization of the project completion time but achieving work continuity which leads to minimizing the overall project cost. In construction projects, the minimization of the cost may be more desirable than the reduction of the project duration. [7]

4.1 CONVERGING PRODUCTION LINES IN RSM

Let us consider a pair of activities, A1 and B1 taken as an example where the link relationship between the activities is finish to start (FTS). The time duration, T, the resource designation, R, the Early Start Day, ESD, and the Early Finish Day, EFD, are as shown in the legend. The values of R are expressed as alphabetic symbols to identify the particular resource being used by the activity.

These two activities are plotted as a bar chart in Figure 4.1(a). They are plotted again in the form of an RSM diagram in Figure 4.1(b). There is only one repetitive unit, and the zero point on the Y-axis is designated by S to indicate the start of the unit. The finish of the unit is designated by F.

The inclined line drawn from the start of Activity A1 in Unit 1 to the finish of Activity A1 in Unit 1 represents the production line for Activity A1. In a similar manner, the production line for Activity B1 is drawn from its start at the end of Day 13 and the

start of the unit to its finish at the end of Day 15 and the finish of the unit. The FTS precedence relationship between the activities is indicated by the dotted arrow at Day 13 drawn downward from the finish of Activity A1 to the start of Activity B1. Note that the unit production rate for Activity A1 is $1/3$ unit per day ($1/3$ u/d), and for Activity B1 is $1/2$ u/d. These rates will be recognized as the mathematical slopes of the respective production lines.

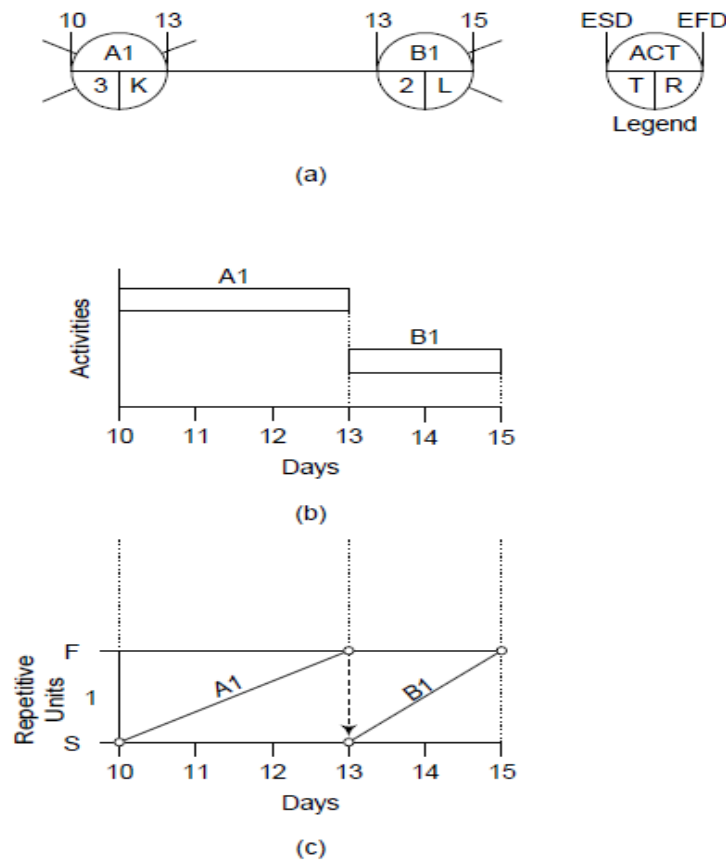


FIGURE 4.1 CONVERGING FTS ACTIVITIES IN RSM

The same pair of activities extended over three repetitive units is plotted in the form of a bar chart in Figure 4.2(a). Each unit contains the two activities, and the numeral associated with each activity identifies the unit in which it is scheduled. Since only technical precedence logic is employed, there is a one day lag between the B activities from one unit to the next.

Figure 4.2(b) shows a unit-by-unit RSM plot of the same activities with the FTS relationships shown by the downward pointing arrows. The production lines plotted for Activities A1 through A3 form a continuous straight line beginning at the end of Day 10 and ending on Day 19. Because each A activity uses Resource K and has a unit production rate of $1/3$ u/d, it follows that the production line for the three A activities also has the same unit production rate of $1/3$ u/d.

The production lines for Activities B1 through B3 do not form a continuous production line when plotted unit by unit because of the lags between the B activities. To make a continuous production line for the B activities and provide for the uninterrupted utilization of resources, the start of Activity B1 must be delayed by two days and the start of Activity B2 must be delayed by one day. The resulting production line for the B activities is shown in Figure 4.2(b) as a dashed line beginning at the end of Day 15 and continuing through Unit 2 then extending as a solid line through Unit 3 to finish on Day 21. Because the unit production rate for each unit's B activity is $1/2$ u/d, the unit production rate of the production line for the B activities is also $1/2$ u/d.

Notice that the two continuous production lines converge toward the finish of Unit 3 because the unit production rate of the B line is greater than that of the A line. Also note that at Day 19 and the beginning of Unit 3, the end of the FTS arrow between the finish of Activity A3 and the start of Activity B3 controls the start of Activity B3, and subsequently, the position of the B line. This location, or control point, has been labeled $cp_F(AB)$ where the subscript, F, stands for finish and signifies the last unit in the sequence, and the letters A and B show the dependency of Activity B upon Activity A. This illustrates a basic RSM principle:

When the unit production rate of an activity's production line is greater than the unit production rate of the preceding activity's production line, the two production lines will tend to converge as the number of units increases. Owing to the desired continuous utilization of resources from unit to unit, this convergence tends to place any dependency control between the activities toward the last unit in the sequence.

With the above principle in mind, a simple procedure for constructing the production line for the B activities suggests itself. First establish the control point $cp_F(AB)$ at the start of Activity B3 and then draw the continuous production line for B through it.

Since Activity B3 is the last activity in the sequence, another control point, called cp_E , at the end of Activity B3 can also serve as a point through which the B production line may be drawn. The two days shown in Figure 4.2(b) between the end of Activity A3 and the end of Activity B3 at cp_E is a lead time, LT, that relates the finish of the B production line to the finish of the A production-line. [13]

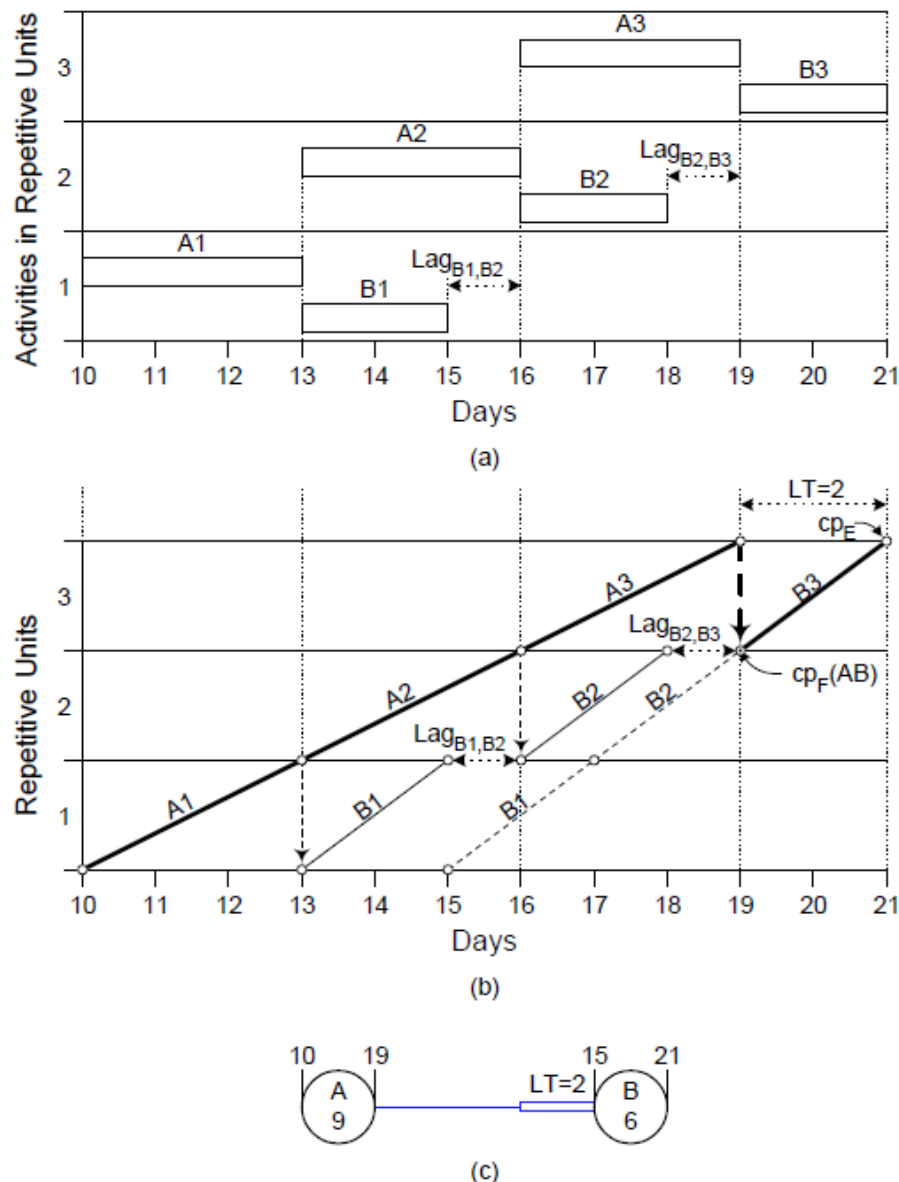


FIGURE 4.2 BAR CHART AND RSM DIAGRAM FOR THREE UNITS WITH CONVERGING FTS ACTIVITIES

4.2 DIVERGING PRODUCTION LINES IN RSM

Figure 4.3(a) is a bar chart of another pair of activities removed from a precedence network for a project. These two activities are extended over three repetitive units with the activities grouped by unit. Each A activity has a duration of 2 days and each B activity has a duration of 3 days. The precedence relationship between the activities in each unit is FTS, and each activity is shown in its scheduled early start position when only technical precedence logic is used. Thus, there is a lag of one day between Activities A2 and B2, and a lag of two days between Activities A3 and B3.

Figure 4.3(b) is an RSM unit-by-unit plot of the same activities, with the FTS relationships indicated by the downward pointing dotted arrows at Days 12, 14, and 16. The lags shown between the finish of each A activity and the start of its related B activity are the same as those shown in Figure 4.3(a). As plotted in Figure 4.3(b), the production lines for both A and B are continuous and ensure the uninterrupted utilization of resources even though no deliberate attempt was made to achieve resource continuity.

Also note that in Figure 4.3(b), the unit production rate of the B production line, 1/3 u/d, is smaller than the unit production rate of the A production line, 1/2 u/d. The two unit production lines therefore diverge and the FTS control between the two is found at Day 12 in Unit 1. This control point is labeled cp_S(AB), where the subscript, S, stands for start and signifies the first unit in the sequence, and the letters A and B show the dependency of Activity B upon Activity A. This illustrates another basic RSM principle:

When the production rate of an activity's production line is smaller than the production rate of the preceding activity's production line, the two production lines will tend to diverge as the number of units increases. Owing to the desired continuous utilization of resources from unit to unit, this divergence tends to place any dependency control between the activities toward the first unit in the sequence.

The two days shown in the figure between the start of Activity A1 and the start of Activity B1 at $cpS(AB)$ is a lead time, LT, that relates the start of the B production line to the start of the A production line. This corresponds to a start-to-start (STS) relationship shown in the equivalent CPM overlapping diagram of Figure 4.3(c) where the lead time for the link between the A and B activities represents the time to accomplish the work required in the A activity before the B activity can begin. In this context, the two day duration of Activity A1 represents the amount of time that must elapse before the start of Activity B1 and sets the lead time at 2 days. Thus, $cpS(AB)$, can be positioned two days after the start of Activity A1. The B line passes through $cpS(AB)$, ends at the finish of Activity B3 on Day 21, and sets the duration of the project at 21 days. [13]

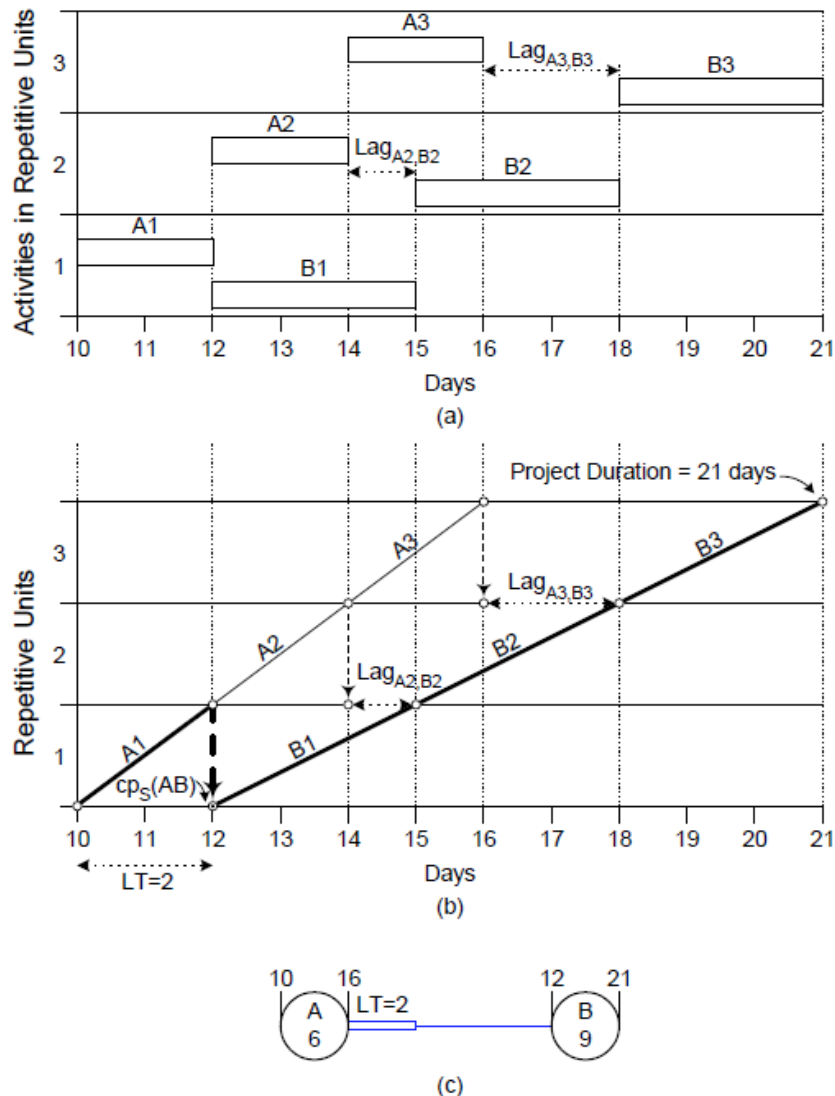


FIGURE 4.3 BAR CHART AND RSM DIAGRAM FOR THREE UNITS WITH DIVERGING FTS ACTIVITIES

4.3 Effects from changing unit production rates on FTS activities

The total duration of the project can be reduced by increasing the unit production rates of various activities. Suppose that the crew for each B activity of Figure 4.3 is increased by fifty percent. This change reduces each B activity duration to two days and increases each unit production rate to $1/2$ u/d, the same as that of each A activity. An RSM diagram for the three units of Figure 4.3(b) with this revised unit production rate is shown in Figure 4.4(a) along with the dashed production line from Figure 4.3(b). The control point, $cpS(AB)$, still controls the position of the B production line which now lies parallel to the line for the A activities. Therefore, increasing the unit production rate of the B production line from $1/3$ u/d to $1/2$ u/d is tantamount to rotating the production line about this control point.

A curved arrow at $cpS(AB)$ signifies this rotation. The project duration is reduced from 21 days to 18 days, and the FTS arrow at the beginning of Activity B3 defines another control point, $cpF(AB)$, through which the new B production line passes. If the resources of each B activity are doubled over those shown in Figure 4.4(a), the unit production rate of the B activities becomes 1 u/d and causes the A and B lines to converge.

A further rotation of the B production line about $cpS(AB)$ would violate the FTS relationships at Days 14 and 16, so the control of the B line must shift to $cpF(AB)$ at the beginning of Unit 3. Figure 4.4(b) shows this shift in control point and the rotation of the B production line about $cpF(AB)$ where the curved arrow refers to the rotation of the line. The B line now begins at the end of Day 14 and sets the project duration at 17 days, one day shorter than in Figure 4.4(a). [13]

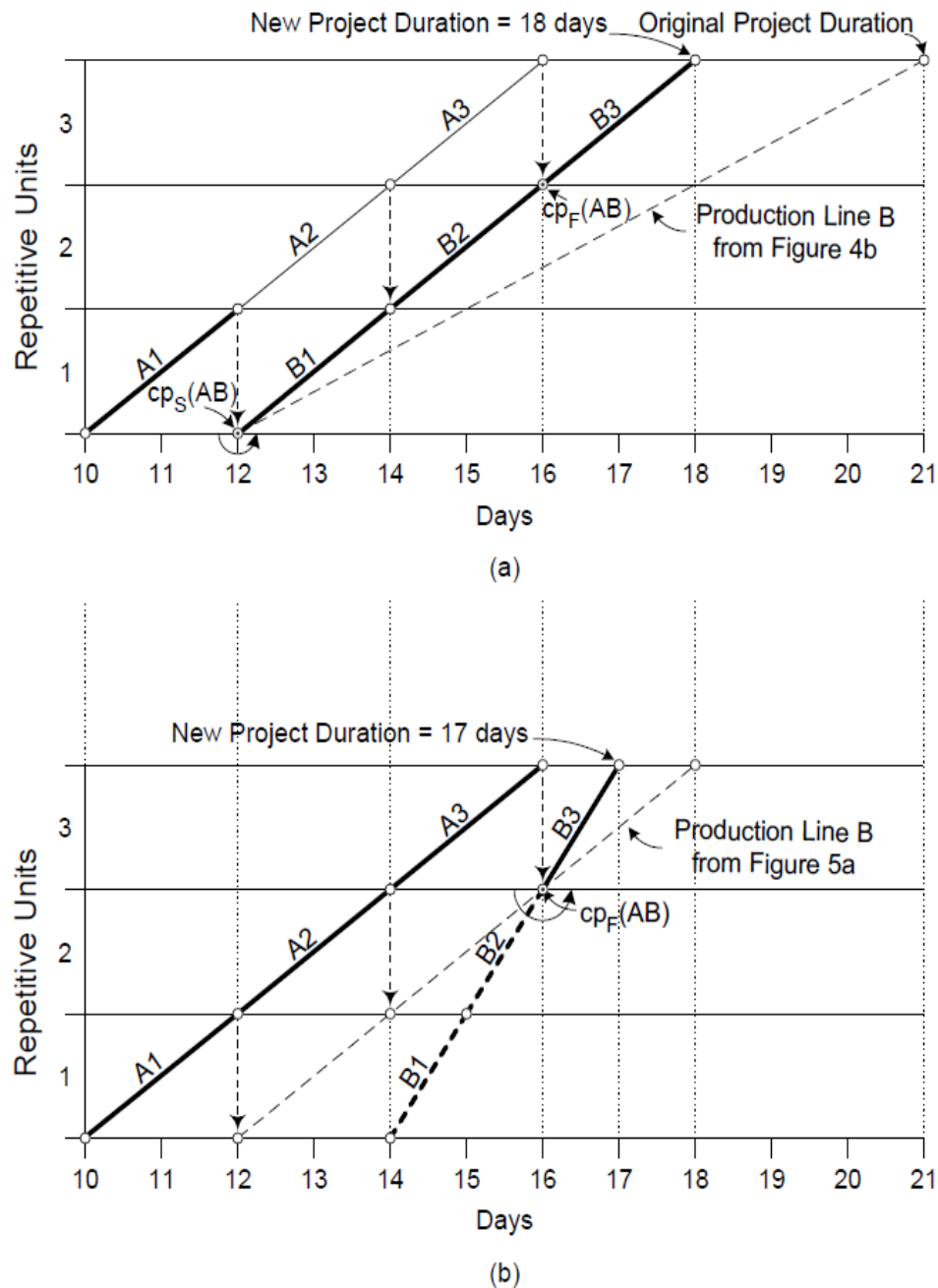


FIGURE 4.4 EFFECTS OF INCREASING UNIT PRODUCTION RATES
IN RSM DIAGRAMS WITH FTS ACTIVITIES

4.4 The Controlling Sequence

In RSM, the chain, or sequence of activities, that establishes the minimum project duration is called the **controlling sequence**. This sequence maintains all technical precedence, resource availability, and resource continuity constraints, and passes through control points which switch the sequence from one production line to the other production line.

In the determination of the controlling sequence, the control point associated with the work content must be used as the point to switch from one production line to the next, because only the work in the lead-time segment can belong to the controlling sequence or to the critical path. [13]

5. SCHEDULE DEVELOPMENT FOR HIGH-RISE BUILDINGS

While high-rise buildings have a large degree of repetition, their scheduling needs are different from either linear projects such as highways and pipelines, or nonlinear projects such as multiple similar houses. This is because high-rise buildings involve repetitive activities that advance within the building not in one direction but in two directions: A horizontal direction through the floor, and a vertical direction from one floor to the next. The sequencing of activities is, therefore, controlled by horizontal and vertical constraints.

5.1 Step-wise procedure for schedule development for high-rise buildings using RSM

The step-by-step procedure for schedule development for high-rise buildings is explained as follows:[13]

Step 1 - The first stage of RSM includes the following five steps:

- (1) In the first stage, activities would be sorted in sequence step order.
- (2) For each predecessor, determine the activity's 'pushed' position based on each relationship (link) in every possible unit.
- (3) For each 'pushed' position, determine the necessary 'shift' to that activity. The shift represents the difference between the shape starting at time zero and the pushed position.
- (4) Select the maximum shift over all units, all incoming relationships, and all predecessors.
- (5) Move the activity being scheduled to the position that results from the maximum shift.

Among all the activities that have to be executed in a high-rise building, the erection of the structure sets the rhythm for the remaining trades. In general, structural-core activities are the columns, beams, and slabs. They have a specific relationship and have to proceed in a specific manner to avoid scheduling errors.

Fig. 5.1, for example, shows an example repetitive schedule for structural core activities along a five-story building. While the figure looks typical, it has a fatal problem with respect to a high-rise building. In the figure, the columns of the 2nd floor are scheduled to start at time Sc_2 before the slab of the first floor is completed at time Fs_1 . This violates the basic logical relationship that columns at the upper floors require the slabs underneath to be completed.

Using this approach, the corrected schedule is shown in Fig. 5.2. As shown, the structural-core group is dealt with as one activity that uses one crew. The structural-core activity in an upper floor starts only after the completion of the whole group at the lower floor. Dealing with the structural core activities in this manner prevents scheduling errors that are specific to high-rise buildings. [1]

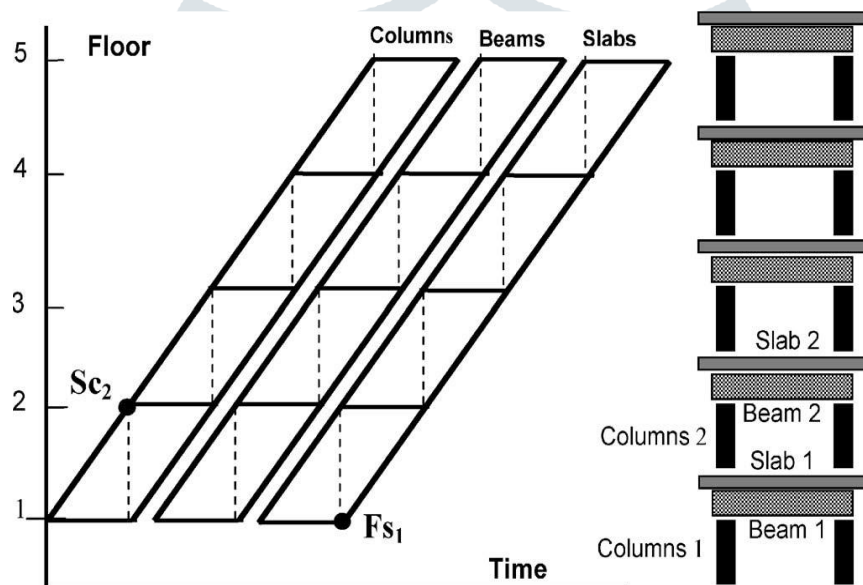


Figure 5.1 Improper scheduling of structural-core activities

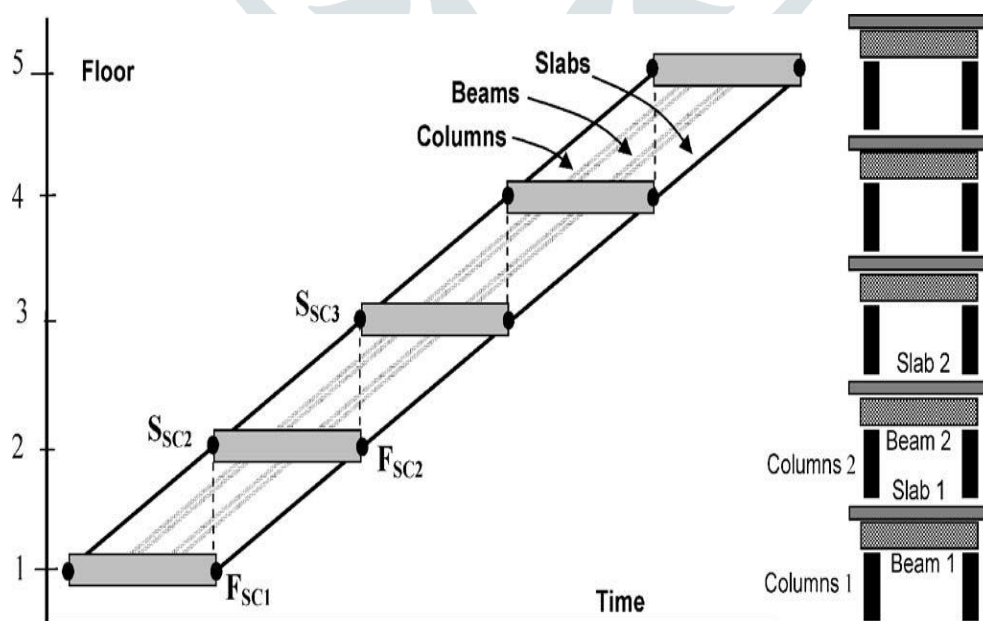


Figure 5.2 Corrected schedule for structural-core activities

Step-2:

The second stage is used to model the pulling effect of work continuity automatically. It is built on an important assumption: each activity would have no more than one 'continuity predecessor'. Note that every activity may have multiple predecessors but only one of the predecessors is linked with a continuity relationship.

The assumption simplifies the calculation and increases the computational efficiency because activities linked by continuity relationships can therefore form a 'continuity activity chain'.

The second stage includes the following steps:

- (1) Locate continuity activity chains and sort them according to the precedence order.
- (2) Increase the start time of the first activity in a continuity activity chain by the sum of lags within the chain and schedule other activities based on the new start time of the first activity.

5.2 WORK BREAKS

5.2.1 Introduction to work breaks

A work break is a predetermined interruption, intentionally scheduled in a resource calendar to relax resource continuity constraints. Applying work breaks properly in repetitive activities could result in an earlier start date of the repetitive activities, which in turn shortens project duration. Scheduling repetitive activities with the Repetitive Scheduling Method (RSM) may sometimes cause increase in the project duration. In certain cases, cost savings from maintaining continuous resource utilization might not favorably compensate for the penalty cost from the lengthened duration. [14]

Figure 5.3 is a production diagram showing the early schedule for four activities (A, B, C, and D) that repeat over 4 identical units. The resource performing Activity B has a total idle time of 30 days from 3 interruptions (LagB1,B2, LagB2,B3, and LagB3,B4). Similarly, Activity D has a total idle time of 45 days, caused by 3 interruptions. Therefore, this early schedule (CPM) results in 75 days of total idle time, where project duration is 105 days.

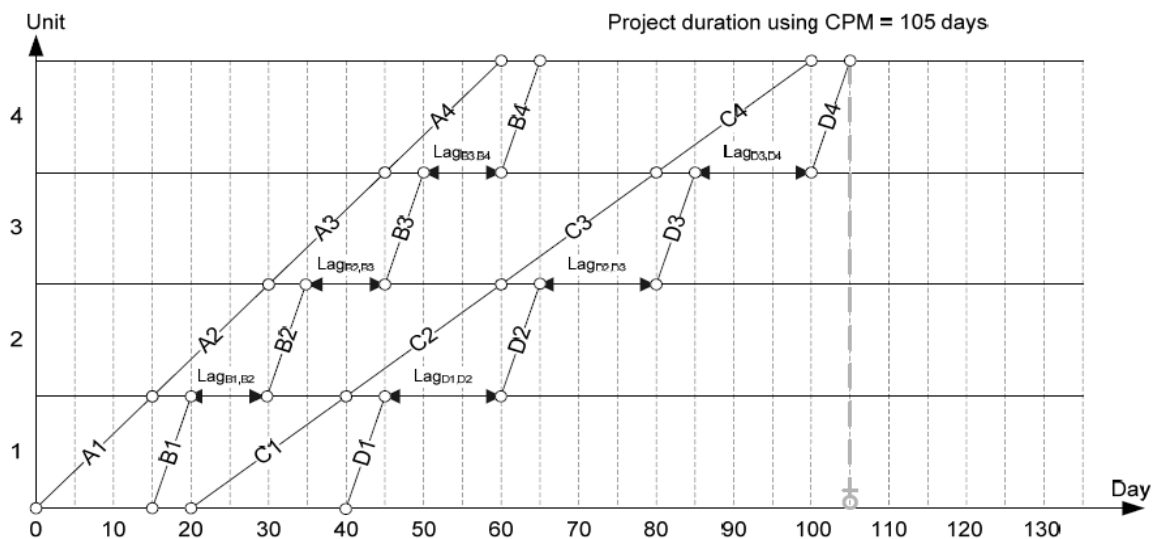


Figure 5.3 CPM schedule with 105-day project duration and 75-day idle time

Figure 5.4 displays a schedule using RSM eliminating idle time by postponing Activities B and D from their early start dates. The resource continuity constraints in the RSM schedule eliminate all 75 days of resource idle time but increase project duration from 105 to 135 days.

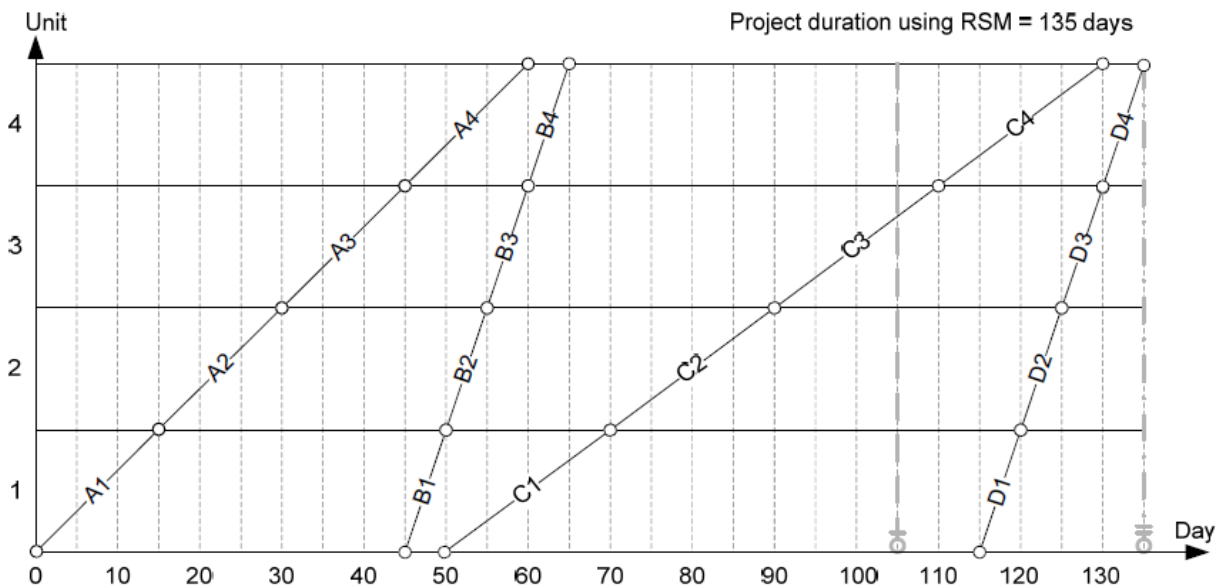


Figure 5.4 RSM schedule with an increased project duration from 105 to 135 days

Typically, the cost savings due to the elimination of resource idle time is far greater than the additional cost from the increased project duration. The tradeoff between eliminating resource idle time and increasing project duration must be analyzed thoroughly.

Figure 5.5 illustrates the tradeoff between project idle time and project duration by introducing one work break in Activity B. In Figure 5.5, introducing a 20-day work break between B2 and B3 reduces project duration from 135 days to 115 days. Notice that in order to maintain resource continuity between B1 and B2, the start of B1 must be postponed from its early start date of day 15 to day 25.

Overall, the introduction of a 20-day work break in activity B reduces project duration also by 20 days, from 135 days to 115 days. This schedule is only 10 days longer than the project duration of 105 days in the CPM schedule, while at the same time it eliminates the 75 days of resource idle time. Thus, the schedule with the work break results in a better solution.

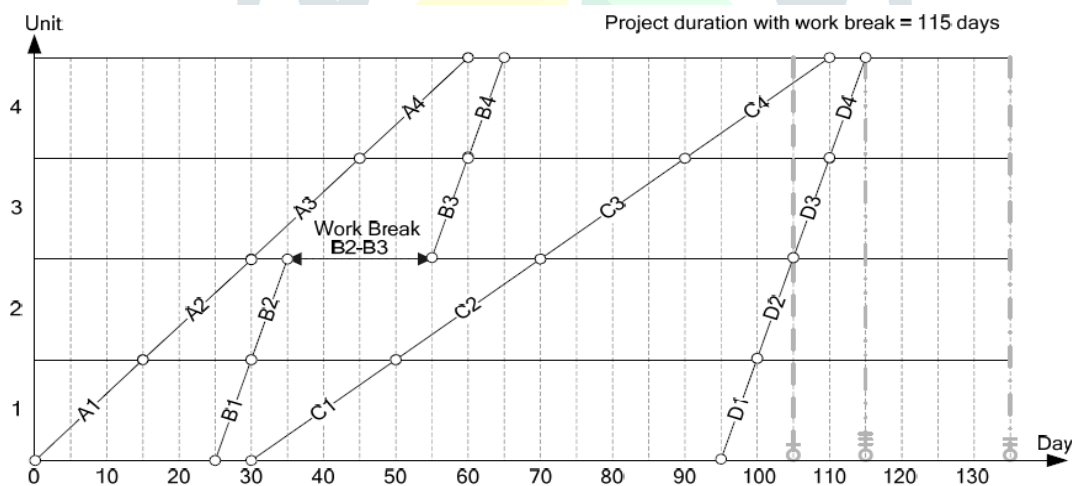


Figure 5.5 The work break B2-B3 reducing project duration from 135 to 115 days

5.2.2 Candidate Work Break Positions

To determine candidate work break positions, the following concepts derived from repetitive scheduling method (RSM) are used:

- 1) Control points and controlling sequences
- 2) Relative production rates

1) Control Points and Controlling Sequences

A control point between two repetitive activities is the precedence constraint that determines the start date of a succeeding repetitive activity under resource continuity constraints. A controlling sequence is a series of activities that controls project duration under resource continuity constraints. It can be determined visually in a production diagram by navigating from project completion to project start through control points.

Only repetitive activities on controlling sequences should be considered as candidates for introducing work breaks. Activities not on the controlling sequences can be ignored. Nevertheless, not every work break position on controlling-sequence activities could shorten project duration. [14]

The effectiveness of work breaks in shortening project duration depends on the relative production rates between activities on the controlling sequence.

2) Relative Production Rates

Positions of control points in the Repetitive Scheduling Method (RSM) are subject to the relative value of production rates between activities. According to RSM, the relative value of production rates between predecessors and successors is characterized as either converging or diverging.

An activity to which work break should be introduced must meet the following criteria.

- 1) It must be on a controlling sequence.
- 2) It must have a converging relationship with its direct predecessor on the same controlling sequence.
- 3) It must have a diverging relationship with its direct successor on the same controlling sequence.

When there is more than one possible work break position, it is necessary to test all the possible positions. The best work break position should result in the greatest decrease in project duration and a small increase project idle time. [14]

6. CASE STUDY

6.1 Project description:

The project taken under study is residential flats situated in kothapet. It is a G+5 building with total number of 20 flats with a count of 4 flats in each floor. The ground floor is left exclusively for parking space. This project is situated in a well connected locality with all the amenities like hospitals, bus routes, schools and restaurants which are available within reach.

6.2 Details about the project:

Area statement:

Flat no: 1 & 2 – 2 BHK – 94.482 sqm

Flat no: 3 & 4 – 2 BHK – 91.974 sqm

Total plot area = 780.68 sqm

Built-up area = 297.22 sqm

Carpet area = 258.15 sqm

The building is surrounded by a 30' wide road on either side. Each apartment has a two bedroom, a living hall and a kitchen. A balcony is attached to one of the bedrooms and utility space is provided outside the kitchen. The provision of 5'x6' is made for the purpose of lift.

For planning of the given project, data collection is the primary task which needs to be done before scheduling of the project. The data collection comprises of collecting of plans and drawings which includes typical floor plan, structural drawing details of footings, columns, beams and slabs.

6.3 Scheduling for the given project

The case study undertaken is scheduled using the repetitive scheduling method (RSM).

The process of scheduling of the given project involves the following steps:

1. calculation of concrete and shuttering quantities:

Firstly, the concrete and shuttering quantities for various items of work are calculated using the center-line method. The calculated shuttering and concrete quantities are shown in Table 6.1 and 6.2 respectively.

Tabel 6.1 Shuttering quantities

SNo	Description of work	Quantity	Unit
1.	Formwork for footings	139.54	Sqm
2.	Formwork for plinth beams	239.40	Sqm
3.	Formwork for columns upto first floor level	208.26	Sqm
4.	Formwork for beams and slabs at ground floor level	311.67	Sqm
5.	Formwork for columns in first floor level	176.59	Sqm
6.	Formwork for beams and slabs at first floor level	311.67	Sqm

Table 6.2 Concrete Quantities

SNo	Description of work	Quantity	Unit
1.	Earthwork excavation	274.83	Cum
2.	P.C.C (1:5:10)	20.32	Cum
3.	R.C.C (M-20 grade) footings	82.51	Cum
4.	R.C.C for columns upto first floor level	21.74	Cum
5.	R.C.C for plinth beam	27.22	Cum
6.	R.C.C for slab at ground floor level	38.83	Cum
7.	R.C.C for columns in first floor	15.34	Cum
8.	R.C.C for beams and slabs at first floor level	68.08	Cum
9.	R.C.C for staircase upto first floor	1.89	Cum
10.	R.C.C (1:2:4) for lintels over doors and windows	2.58	Cum
11.	Brick masonry with C.M (1:8) in the first floor	182.7	Cum
12.	Brick masonry with C.M (1:8) in the parapet wall	14.48	Cum
13.	Brick masonry with C.M (1:4) for steps in the staircase	0.77	Cum
14.	Plastering with C.M (1:4) for walls and ceilings	1615.94	Sqm
15.	Plastering with C.M (1:4) for parapet walls	120.66	Sqm
16.	Plastering with C.M (1:5) for steps in the staircase	9.61	Sqm
17.	Flooring with C.M (1:3) in first floor	326.78	Sqm
18.	Flooring with C.M (1:3) in first floor landing in the staircase	6.33	Sqm
19.	White wash for ceilings and walls in the first floor	548.11	Sqm

2. Calculation of reinforcement details

The reinforcement details of structural core activities like footings, columns, beams and slabs are worked out by preparing their respective bar-bending schedule. The calculated reinforcement details are shown in Table 6.3.

Table 6.3 Reinforcement details

SNo	Description of work	Quantity	Unit
1.	Quantity of reinforcement required in footings	3349.11	kgs
2.	Quantity of reinforcement required in plinth beams	3948.86	kgs
3.	Quantity of reinforcement required in columns upto first floor level	5530.00	kgs
4.	Quantity of reinforcement required in beams and slabs at ground floor level	7387.50	Kgs
5.	Quantity of reinforcement required in columns at first floor level	4325.75	Kgs
6.	Quantity of reinforcement required in beams and slabs at first floor level	7387.50	Kgs

3. Calculation of duration of various activities

Based on the above quantities calculated, the duration of various activities is worked out by using the labour productivity data taken from the IS 7272 (Part-1) –1974 (Indian Standard-Recommendation for labour output constants for building work). The duration of various items of work calculated is shown in Table 6.4.

Table 6.4 Duration required for various activities

SNo	Activity Description	Duration (days)
1.	Earthwork excavation	18
2.	P.C.C bed	5
3.	Footings	12
4.	Plinth beam	15
5.	Columns upto first floor level	14
6.	Beams and slabs at ground floor level	15
7.	Columns at first floor level	12
8.	Beams and slabs at first floor level	15
9.	Brick work for walls in first floor	20
10.	Plastering work for walls and ceilings in first floor	18
11.	Floor finish in first floor	14
12.	White-wash for walls and ceilings in first floor	10

4.Preparation of CPM schedule

After the calculation of durations, CPM schedule is prepared before the preparation of RSM schedule. Let us consider six repeating activities A, B, C, D, E & F for the project taken under consideration. The description of activities and their precedence relationship is shown in Table 6.5.

The CPM schedule is prepared considering the precedence relationship and the duration of various activities. The CPM diagram is plotted taking duration on X-axis and repetitive units on Y-axis. Figure 6.1 shows the CPM schedule with 197 day project duration.

Table 6.5 Precedence relationship

Activity name	Activity Description	Predecessor
A	Columns in the floor considered	-
B	Beams and slab for the floor considered	A
C	Brick-work for walls	B
D	Plastering work for walls and ceilings	C
E	Floor finish	D
F	White-wash for walls and ceilings	E

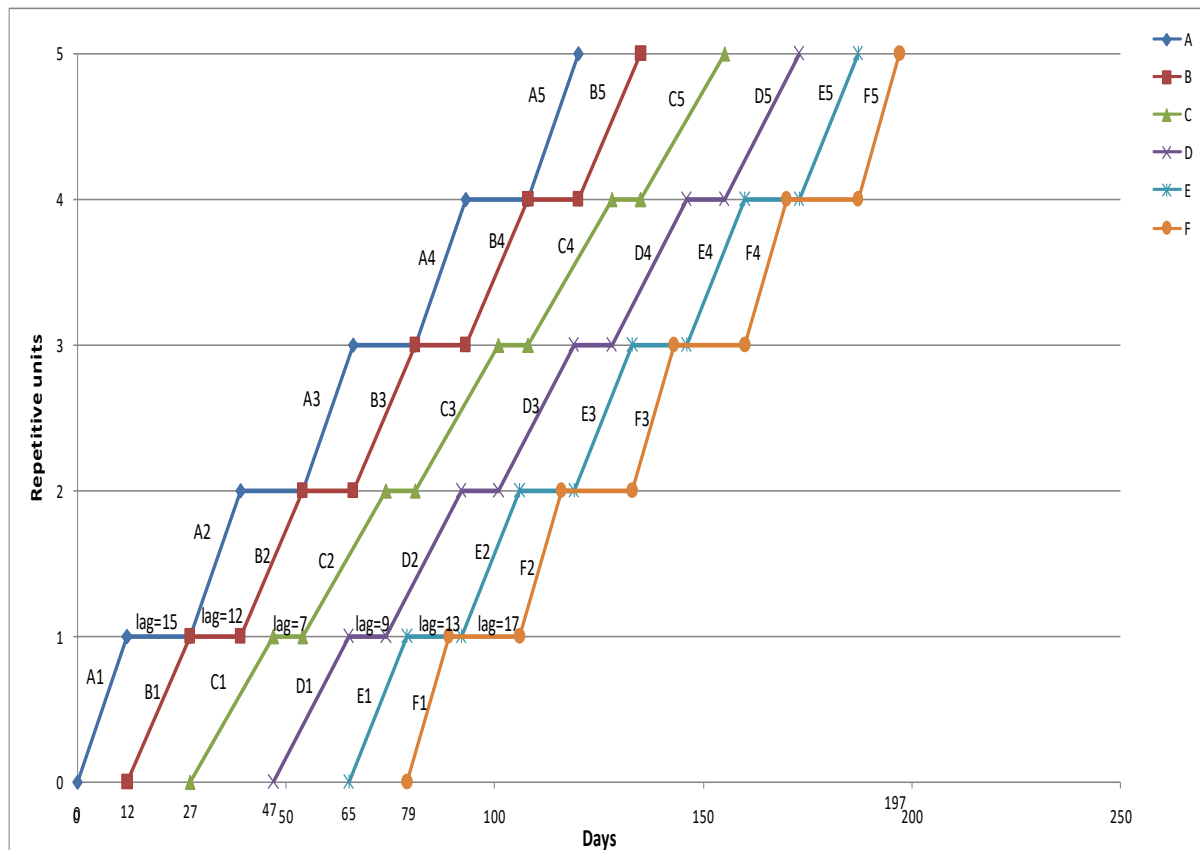


Figure 6.1 CPM schedule with 197 day project duration

5. Preparation of RSM schedule

The repetitive scheduling method cannot be applied to activities A & B. The reason is that the activities A & B are structural core activities and the columns of the next floor cannot start unless the slab of the previous floor is completed, i.e. A2 cannot start unless B1 is completed. Activities A & B are related in two ways:

- Activity B1 can start only after activity A1 is completed.
- Activity A2 cannot start unless activity B1 is completed.

The unit production rates of the six repeating activities is shown in Table 6.6

Activity name	Unit production rate (upr)
A	1/12
B	1/15
C	1/20
D	1/18
E	1/14
F	1/10

The repetitive scheduling method is applied to activities C, D, E & F. The start of the considered activity is pushed by the amount of total lag time of that particular activity until there is no more resource idle-time. The start of the activity 'C' is pushed from day 27 to day 55. Similarly, the start of activity 'D' is pushed from day 47 to day 83. The start of activities 'E' and 'F' are pushed from day 65 & day 79 to day 117 & day 147 respectively.

The total resource idle time eliminated in

- Activity C = 28 days
- Activity D = 36 days
- Activity E = 52 days
- Activity F = 68 days

A total resource idle time of 184 days can be eliminated by the application of RSM. The total duration of the project remains same. Figure 6.2 shows the RSM schedule with 197 day project duration.

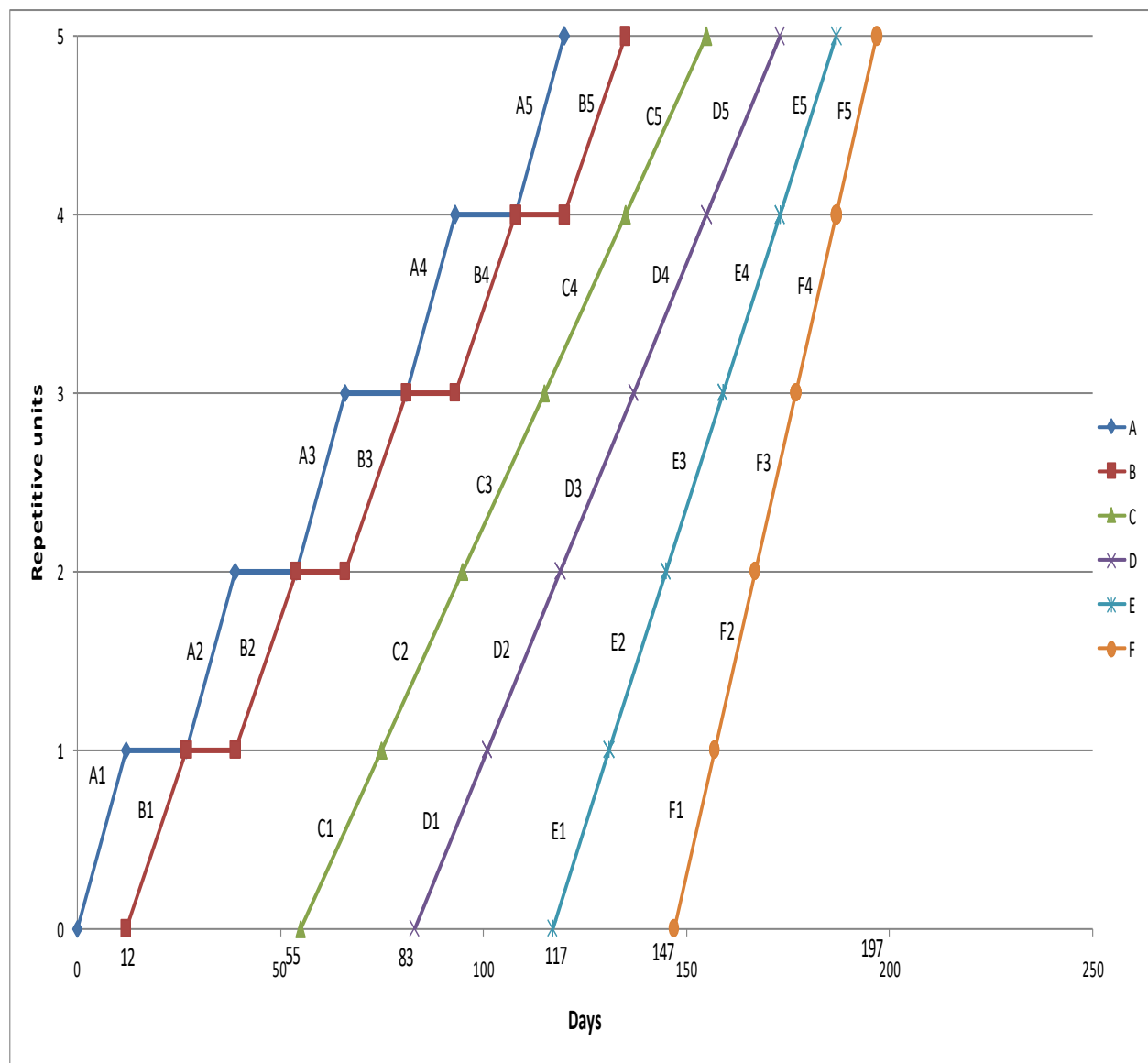


Figure 6.2 RSM schedule with 197 day project duration

6.4 Controlling Sequence

In RSM, sequence of activities that establishes minimum project duration is called the controlling sequence. The controlling sequence for the above RSM schedule can be determined as follows :

- As unit production rate of activity 'C' is less than the unit production rate of activity 'B', the control point passes from the end of activity B's first unit to the start of activity C's first unit.
- As unit production rate of activity 'D' is greater than the unit production rate of activity 'C', the control point passes from the end of activity C's last unit to the start of activity D's last unit.
- As unit production rate of activity 'E' is greater than the unit production rate of activity 'D', the control point passes from the end of activity D's last unit to the start of activity E's last unit.
- As unit production rate of activity 'F' is greater than the unit production rate of activity 'E', the control point passes from the end of activity E's last unit to the start of activity F's last unit.

The controlling sequence for the given RSM schedule is found by joining the obtained control points. For the given schedule, the controlling sequence is

C1-C2-C3-C4-C5-D5-E5-F5

6.5 Reducing the project duration

Minimum project durations can be achieved by adding resources to some activities and subtracting resources from others until all unit production lines have the same unit production rate and are parallel to each other.

In the case study considered, it is observed that the activities 'C' & 'D' are the major contributors for the 197 day project duration. So it appears that the total duration of the project can be reduced if the unit production rate of these two production lines is increased.

6.5.1 Rotating multiple production lines

In order to reduce the total project duration, unit production rate of activity 'C' is increased from 1/20 to 1/15 and unit production rate of activity 'D' is increased from 1/18 to 1/14. By changing the unit production rate of activities 'C' and 'D', the total project duration is reduced by 9 days.

The increase in the unit production rate depends on the availability of the resources i.e availability of labour, equipment and funds. The resource availability needs to be checked before the unit production rate of activities is increased.

Proper planning is required in order to balance the cost of adding resources with that of the reduction in project duration. The cost saved due to decrease in project duration should be compared with that of the cost of adding resources in order to increase the unit production rate. If the cost of adding resources turns out to be more than the indirect cost savings due to decrease in project duration, then it is not feasible to increase the unit production rate. Figure 6.3 shows the CPM schedule with a reduced project duration of 188 days.

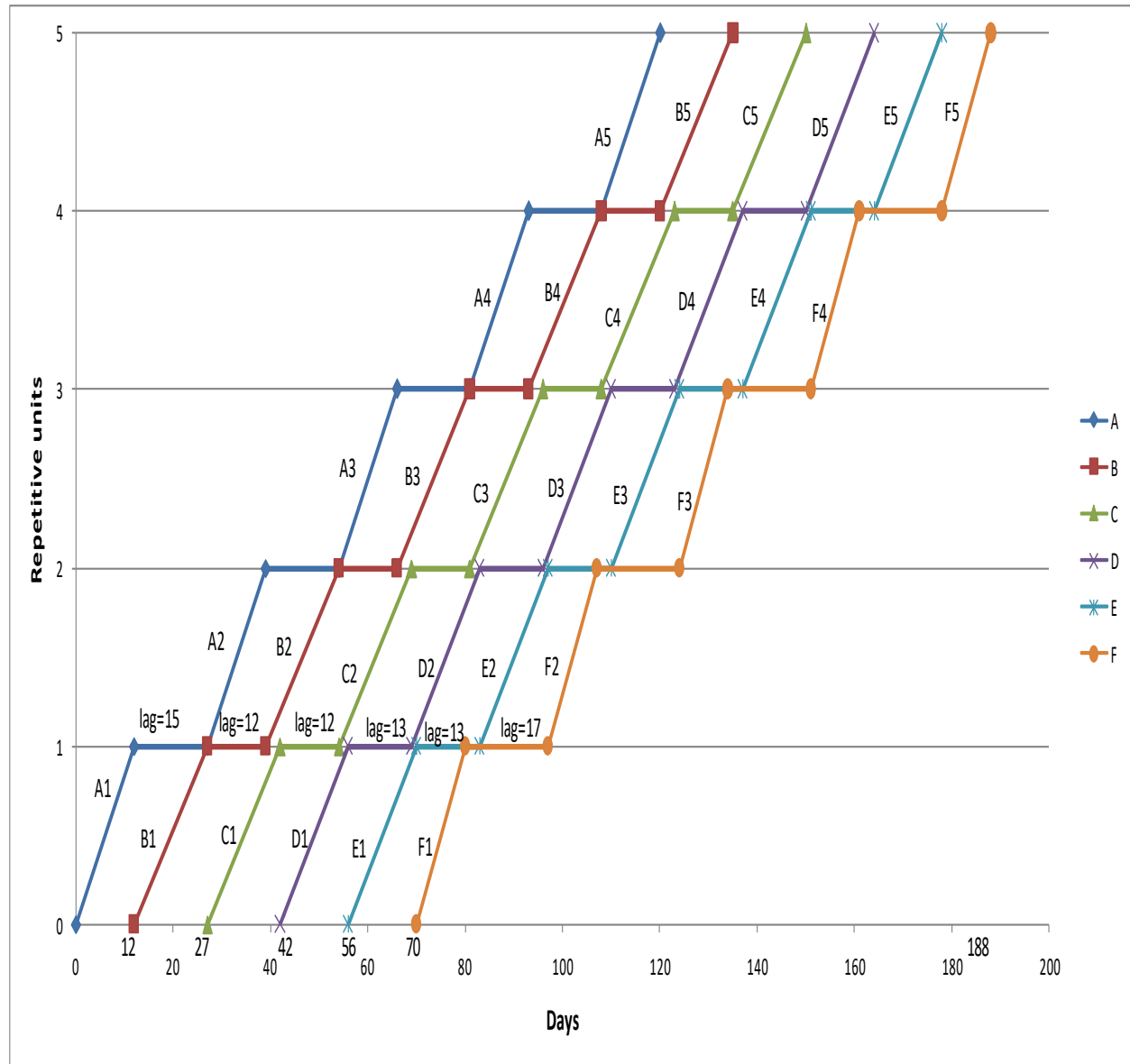


Figure 6.3 CPM schedule with a reduced project duration of 188 days

6.5.2 Preparation of RSM schedule

Now, the unit production rate of activity 'C' is 1/15 and that of activity 'D' is 1/14. The unit production rate of remaining activities remain same. RSM is applied as usual to activities C, D, E & F. The start of the activity 'C' is pushed from day 27 to day 75. Similarly, the start of activity 'D' is pushed from day 42 to day 94. The start of activities 'E' and 'F' are pushed from day 56 & day 70 to day 108 & day 138 respectively.

The total resource idle time eliminated in

- Activity C = 48 days
- Activity D = 52 days
- Activity E = 52 days

- Activity F = 68 days

A total resource idle time of 220 days can be eliminated by the application of RSM. The total duration of the project remains same. Figure 6.2 shows the RSM schedule with 188 day project duration.

6.5.3 Controlling Sequence

The controlling sequence remains same even though the unit production rate of activities 'C' and 'D' are changed for the case study considered. It may not be true for all the cases. The controlling sequence may or may not change if the unit production rates of activity is increased or decreased. In the project considered, increasing the unit production rate of activities 'C' and 'D' doesn't change the controlling sequence, i.e. the controlling sequence remains same, i.e.

C1-C2-C3-C4-C5-D5-E5-F5

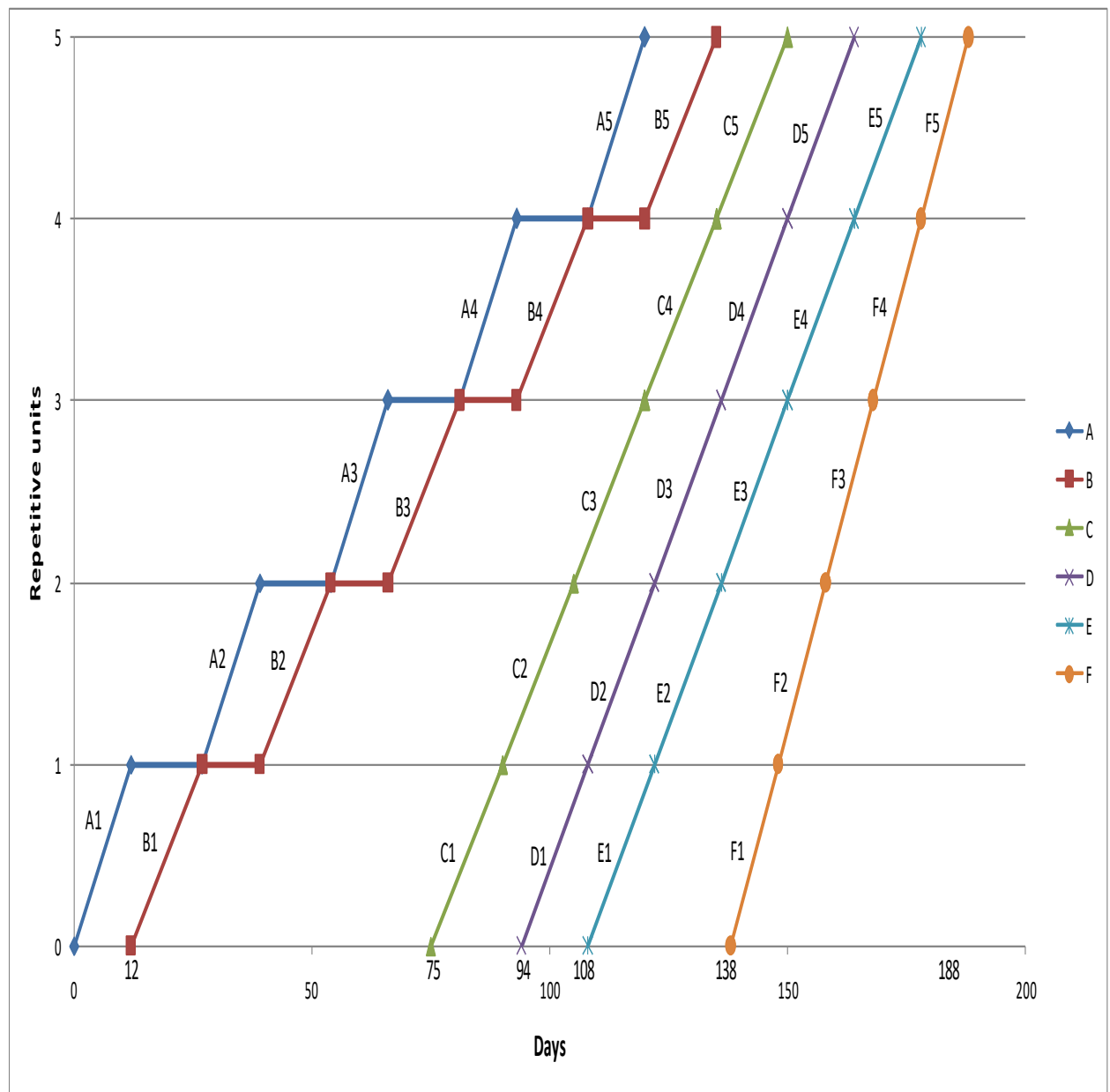


Figure 6.4 RSM schedule with a reduced project duration of 188 days

6.6 Effects from changing unit production rates

Suppose that the crew of 'D' activity is increased by 50%, this change reduces each 'D' activity duration to 9 days and increases its unit production rate to 1/9. Figure 6.5 shows the CPM schedule with a reduced project duration of 188 days.

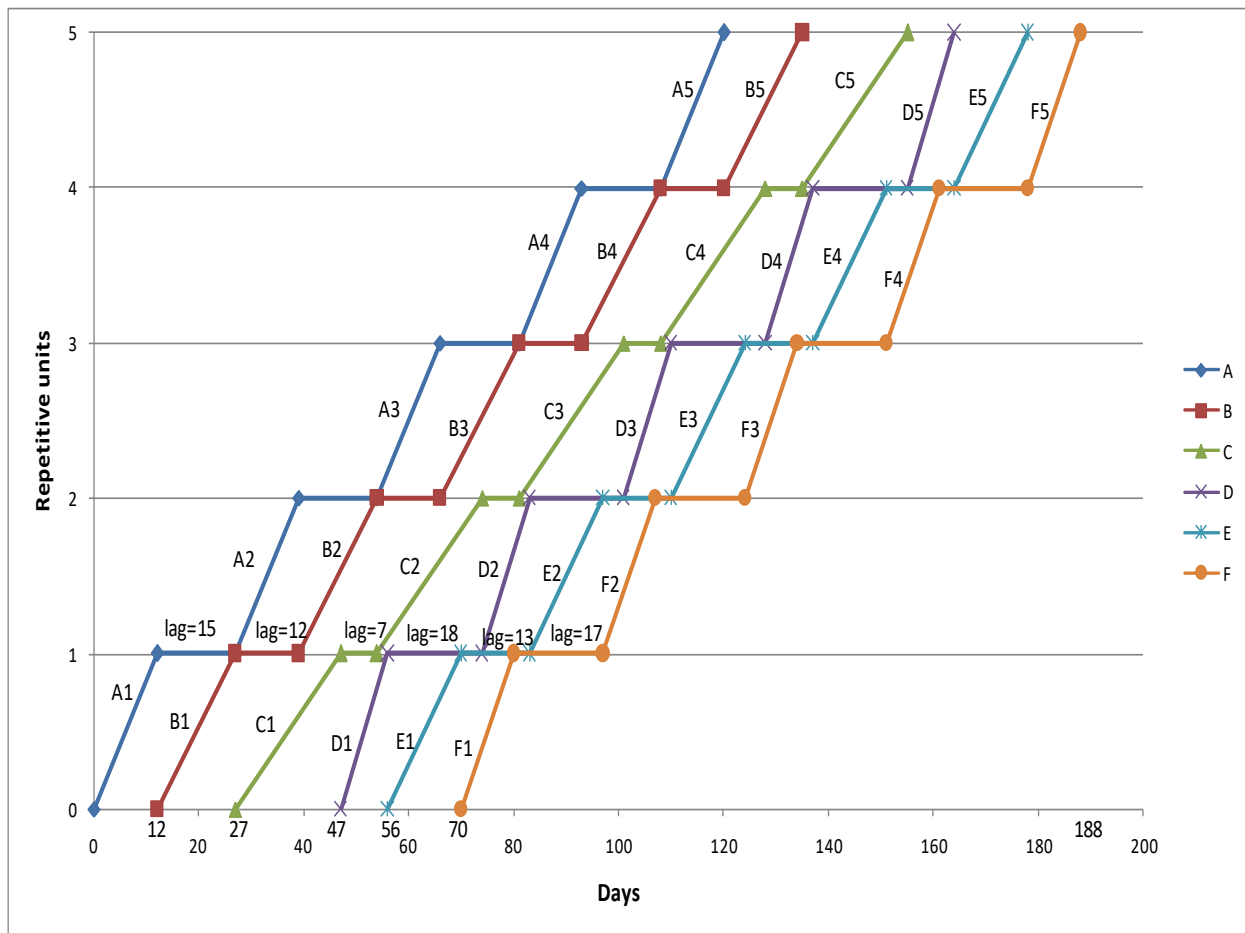


Figure 6.5 CPM schedule with a reduced project duration of 188 days

6.6.1 Preparation of RSM schedule

Now, the unit production rate of activity 'D' is 1/9. The unit production rate of remaining activities remain same. RSM is applied as usual to activities C, D, E & F. The start of the activity 'C' is pushed from day 27 to day 55. Similarly, the start of activity 'D' is pushed from day 47 to day 119. The start of activities 'E' and 'F' are pushed from day 56 & day 70 to day 128 & day 158 respectively.

The total resource idle time eliminated in

- Activity C = 28 days
- Activity D = 72 days
- Activity E = 52 days
- Activity F = 68 days

A total resource idle time of 220 days can be eliminated by the application of RSM. The total duration of the project increases by 20 days after the application of RSM. Figure 6.6 shows the RSM schedule with an increased project duration of 208 days.

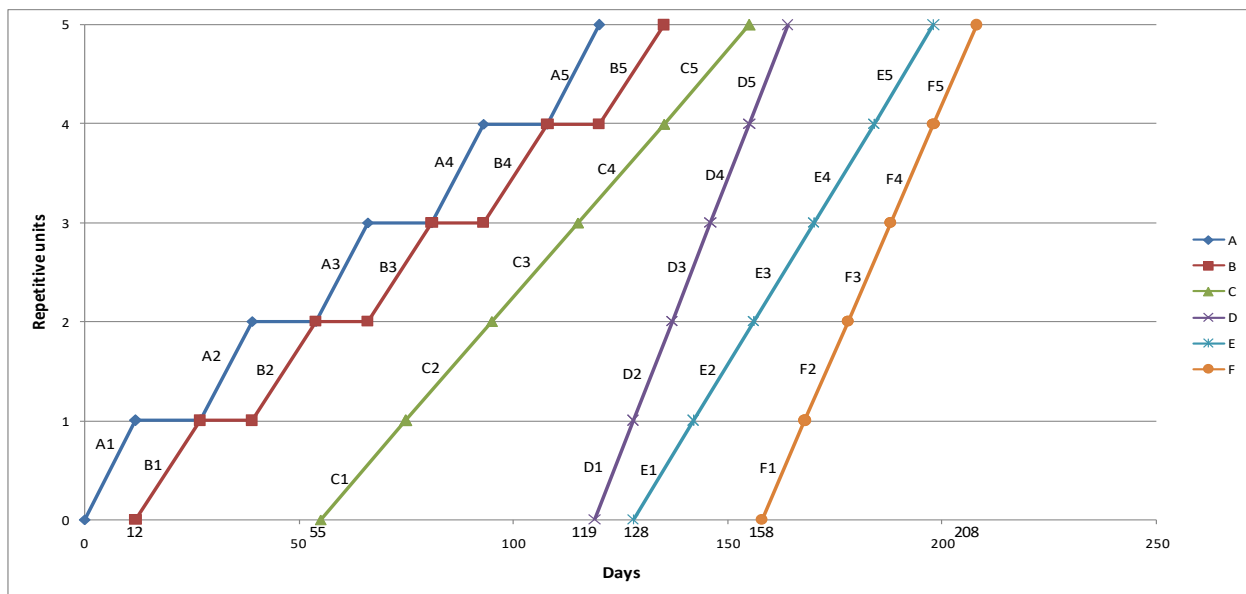


Figure 6.6 RSM schedule with an increased project duration of 208 days

6.6.2 Controlling Sequence :

The controlling sequence changes in the above case as the unit production rate of 'D' is changed. The controlling sequence for the revised RSM schedule can be determined as follows :

- As unit production rate of activity 'C' is less than the unit production rate of activity 'B', the control point passes from the end of activity B's first unit to the start of activity C's first unit.
- As unit production rate of activity 'D' is greater than the unit production rate of activity 'C', the control point passes from the end of activity C's last unit to the start of activity D's last unit.
- As unit production rate of activity 'E' is less than the unit production rate of activity 'D', the control point passes from the end of activity D's first unit to the start of activity E's first unit.
- As unit production rate of activity 'F' is greater than the unit production rate of activity 'E', the control point passes from the end of activity E's last unit to the start of activity F's last unit.

The controlling sequence for the given RSM schedule is found by joining the obtained control points. For the given schedule, the controlling sequence is

C1-C2-C3-C4-C5-D4-D3-D2-E1-E2-E3-E4-E5-F5

6.6.3 Applying work breaks :

Applying work breaks properly in repetitive activities could result in an earlier start date of the repetitive activities, which in turn shortens project duration. In the above case, work break is applied in order to reduce the total project duration. The following rules must be followed in determining candidate positions of work breaks:

- a) It must be on the controlling sequence. Activities C1-C5, D2-D4, E1-E5 & F5 are on the controlling sequence.
- b) It must have a converging relationship with its direct predecessor and a diverging relationship with its direct successor on the same controlling sequence. Activity 'D' satisfies the above criteria as it has converging relationship with its predecessor 'C' and diverging relationship with its successor 'E'.

Therefore, there are two possible work break positions, i.e D2-D3 & D3-D4. The best work break position should result in the greatest decrease in project duration and a small increase in project idle time.

Case 1 :

If work break is applied at position D2-D3, then the activity 'D' starts on day 86. The calculated work break duration is found out to be 33 days satisfying all the precedence constraints. The project duration is reduced by 10 days, i.e from day 208 to day 198 from the original RSM schedule. Figure 6.7 shows the RSM schedule with work-break position at D2-D3 and total project duration of 198 days. In this schedule, the total resource idle time eliminated is 187 days with an increase in project duration of 10 days from 188 days to 198 days from the original CPM schedule.

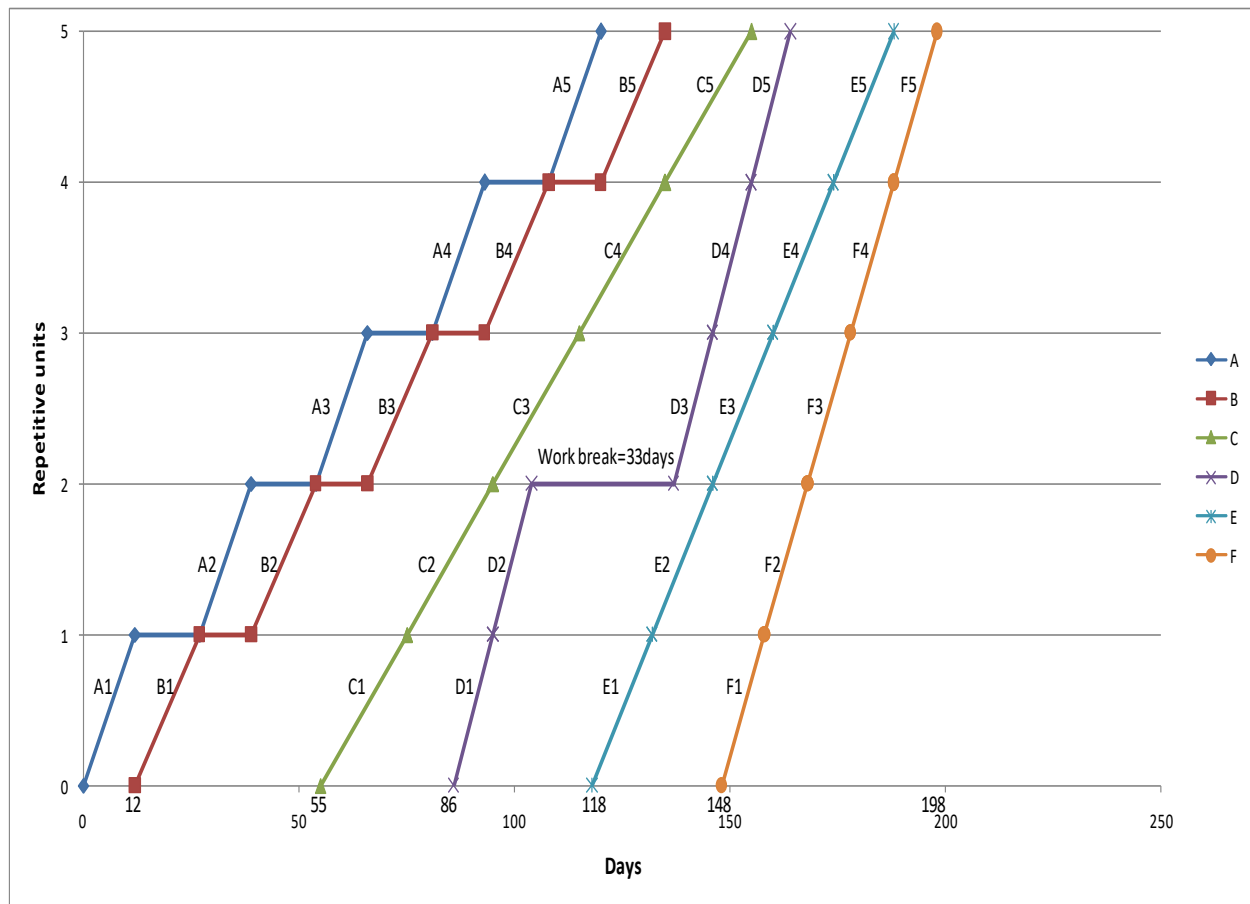


Figure 6.7 RSM schedule with work-break position at D2-D3 and total project duration of 198 days

Case 2 :

If work break is applied at position D3-D4, then the activity 'D' starts on day 97 for the new work break position. The calculated work break duration is found out to be 22 days satisfying all the precedence constraints. The project duration is reduced by 15 days, i.e from day 208 to day 193 from the original RSM schedule. Figure 6.8 shows the RSM schedule with work-break position at D3-D4 and total project duration of 193 days. In this schedule, the total resource idle time eliminated is 198 days with an increase in project duration of 5 days from 188 days to 193 days from the original CPM schedule.

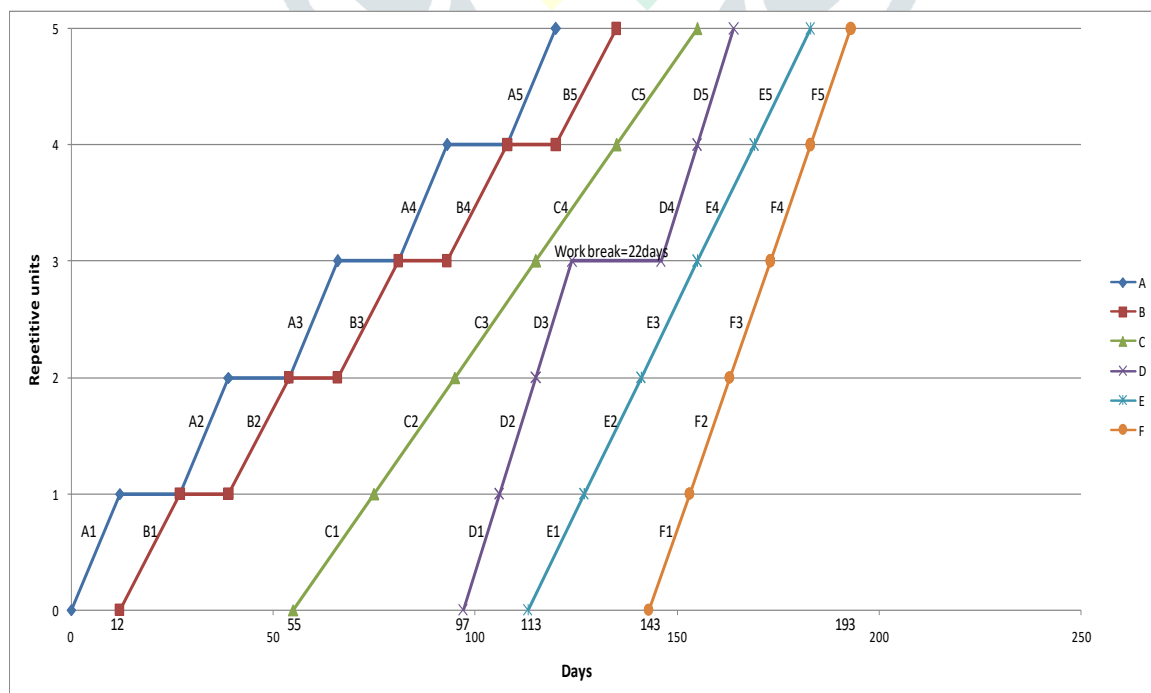


Figure 6.8 RSM schedule with work-break position at D3-D4 and total project duration of 193 days

Tradeoffs between maintaining and relaxing resource continuity constraints must be carefully studied in terms of project cost and duration. The best work break position should result in the greatest decrease in project duration and a small increase in project idle time.

From the above analysis, it can be concluded that work break at D3-D4 provides a better solution as this schedule is only five days longer than the project duration of 188 days in the CPM schedule, while at the same time it eliminates 198 days of resource idle time. Thus, the schedule with a work break results in a better solution.

7. CONCLUSIONS

7.1 Summary

Repetitive projects are those characterized by repetitive construction activities. Examples are highway, pipeline, high-rise building construction, etc. Repetitive projects require schedules that ensure the uninterrupted usage of resources from a unit to similar units in a repetitive activity while maintaining logical dependency constraints. The critical path method (CPM) is the most widely used and accepted planning and scheduling method for traditional (non-repetitive) projects. However, CPM does not suit the planning and scheduling needs of repetitive projects.

The Repetitive Scheduling Method (RSM) recognizes the additional resource continuity constraint that cannot be shown in a CPM network, and thus provides for continuous resource usage. It incorporates commonly accepted activity precedence concepts from CPM, and can be applied to both vertical and horizontal projects that may contain either discrete or continuous activities.

An RSM schedule is presented graphically as an X-Y plot of unit production lines that continue across designated units of the project. One axis of the plot represents units and the other time, and the repetitive units may be assigned to either axis depending on the type of construction project undertaken.

The construction of RSM schedules involves the positioning of successive unit production lines by using the new concept of control points. There is a specific point along each production line that controls the schedule position of its successor production line. This point, called a control point, tends to be located toward the first unit in the sequence of units if the lines diverge, and toward the last unit in the sequence if the lines converge. These control points have significance in the determination of the project duration, and serve as points of rotation for unit production lines whose resource rates are increased or decreased.

RSM also introduces a new concept for the determination of the project duration. As with all projects, the duration must be determined by some sequence of activities that extends from project start to project finish. This sequence in RSM is called the controlling sequence and includes the activities of the first production line from project start until the first control point is reached. It then switches to the next production line and includes all activities on that line until the next control point is found. The sequence continues to include activities switching from one production line to another production line at control points, until reaching the end of the project. An RSM controlling sequence may include both critical and non critical activities. Conversely, activities can be critical because of resource continuity (resource critical), and thus not be part of the controlling sequence.

The unit production rate of any activity can be increased or decreased by altering the composition of the crews or equipment needed to carry out the activity. This causes the associated unit production line to rotate about a control point and to increase or decrease the project duration. However, care must be taken in choosing the activity and resource to change; a poor choice may shift the location of the controlling point for the production line and result in an unexpected project length.

7.2 Conclusions

RSM is a practical scheduling methodology. It uses customary work methods and crews to define repetitive activities that can be arranged in any desired pattern. RSM diagrams are easy to prepare and understand, and the unique concepts of control points and controlling sequence are quickly comprehended. Thus, RSM has all the necessary performance characteristics to serve as a convenient and practical tool for scheduling multi-unit projects.

In this thesis, a plan of 5-storeyed building is considered in order to represent how RSM can help in achieving work continuity. It has been observed that by using RSM, it is possible to eliminate the total resource idle time of 184 days. The total cost of the project also gets reduced as the total idle time of the resources is eliminated.

The total project duration can also be reduced by changing the unit-production rates of various activities. The increase in the unit production rate depends on the availability of the resources i.e availability of labour, equipment and funds. The resource availability needs to be checked before the unit production rate of activities is increased.

Proper planning is required in order to balance the cost of adding resources with that of the reduction in project duration. The cost saved due to decrease in project duration should be compared with that of the cost of adding resources in order to increase the unit production rate. If the cost of adding resources turns out to be more than the indirect cost savings due to decrease in project duration, then it is not feasible to increase the unit production rate.

In the case study taken, it has been observed that by changing the unit production rate of activities 'C' and 'D', we were able to reduce the total project duration by 9 days and eliminate the total resource idle-time of 220 days by the application of RSM.

It has been observed that by increasing the unit production rates of certain activities, the total project duration may be increased after the application of RSM. In such cases, there is a need to apply necessary work breaks in order to decrease the total project duration. Tradeoffs between maintaining and relaxing resource continuity constraints must be carefully studied in terms of project cost and duration. The best work break position should result in the greatest decrease in project duration and a small increase in project idle time.

In the case study taken, it has been observed that by increasing the unit production rate of activity 'D', the total project duration is increased by 20 days from the original CPM schedule after the application of RSM. Therefore, work break is applied in order to relax the resource continuity constraint. From the above analysis, it can be concluded that work break at D3-D4 provides a better solution as this schedule is only five days longer than the project duration of 188 days in the CPM schedule,

while at the same time it eliminates 198 days of resource idle time. Thus, the schedule with a work break results in a better solution.

REFERENCES

1. Tarek Hegazy, M and Ehab Kamarah (2008) – “Efficient Repetitive Scheduling for High-Rise Construction” - Journal Of Construction Engineering And Management.
2. Robert B. Harris and Photios G. Ioannou (1998) – “Scheduling projects with repeating activities” - Journal Of Construction Engineering And Management.
3. Rehab M. Reda (1990) – “RPM : Repetitive Project Modeling” - Journal Of Construction Engineering And Management.
4. Arash Ranjbaran (2007) – “Planning and control of high-rise building construction” – Project Report, Concordia University, Canada.
5. Bin Cheng (2005) – “Limitations of existing scheduling tools in planning utility line construction projects” – Project Report, University Of Florida, U.S.A.
6. Mohammad A. Ammar (2013) – “LOB and CPM Integrated Method for Scheduling Repetitive Projects” - Journal Of Construction Engineering And Management.
7. I-tung yang and Photios G. Ioannou (1998) – “Resource-driven scheduling for repetitive projects: a pull-system approach” – Journal Of Construction Management And Economics.
8. Pandelis G.Ipsilandis (2006) – “Multi-objective optimization in linear repetitive project scheduling” – Operational Research - An International Journal – Vol.6, No-3, pp. 255-269.
9. Tarek Hegazy and Nagib Wassef (2001) – “Cost optimization in projects with repetitive non-serial activities” - Journal Of Construction Engineering And Management.
10. Osama Moselhi and Khaled El-Rayes (1993) – “Scheduling of repetitive projects with cost optimization” - Journal Of Construction Engineering And Management
11. Rong-yau Huang and Kuo-Shun Sun (2006) – “Non-Unit-Based Planning and Scheduling of Repetitive Construction Projects” - Journal Of Construction Engineering And Management.
12. Pasit Lorterapong – “Constraint-Directed Scheduling for Multi-Storey Building Projects” – 13th ISARC (International Symposium On Automation And Robotics In Construction And Mining).
13. I-Tung Yang and Photios G. Ioannou (2004) – “Scheduling system with focus on practical concerns in repetitive projects” – Construction Management And Economics (22) pp:619-630.
14. Charchrist Srisuwanrat (2009) – “The Sequence Step Algorithm- A simulation-based scheduling algorithm for repetitive projects with probabilistic activity durations” – Project Report, University Of Michigan, U.S.A.
15. Marco A. Bragadin (2011) – “Heuristic solution for resource scheduling for repetitive construction projects” - Management and Innovation for a Sustainable Built Environment - 20 – 23 June 2011, Amsterdam, The Netherlands.
16. Mohammed F. Al Helou (2006) – “The impact of continuous resource utilization on cost and duration of projects with repetitive activities using simulation” – Project Report, Construction Management Department, The Islamic University, Gaza.
17. Lihui Zhang, Chuyun Pan, and Xin Zou (2013) – “Criticality comparison between the repetitive scheduling method and the network model” - Journal Of Construction Engineering And Management.
18. Mohammad A. Ammar and Emad Elbeltagi (2001) – “Algorithm for determining controlling path considering resource continuity” - Journal Of Computing In Civil Engineering.
19. Khaled A. El-Rayes (1997) – “Optimized scheduling for repetitive construction projects” – Project Report, Concordia University, Canada.
20. Jianxun Qi and Lihui Zhang (2012) – “Controlling path and controlling segment analysis in repetitive scheduling method” - Journal Of Construction Engineering And Management.
21. IS 7272 (Part-1) – 1974 – Indian Standard recommendation for labour output constants for building work.