STOCHASTIC ANALYSIS ON PROJECT DURATION UNDER THE REQUIREMENT OF CONTINUOUS RESOURCE UTILIZATION

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ABSTRACT

In repetitive construction projects (e.g., multistory buildings, pipelines, and highways), resources (labor and equipment) perform work and move from one repetitive unit to the next. The Repetitive Scheduling Method (RSM) has been proposed to ensure the continuous utilization of resources from unit to unit, which meets the goal of eliminating waste (i.e., unproductive idleness between units) in Lean Construction. This paper demonstrates possible cost-saving benefits associated with continuous resource utilization. Having resources work continuously, however, may require postponements on the start time of resources in certain units. The resulting RSM schedule possesses fewer floats than the early schedule in the Critical Path Method (CPM). The impact of continuous resource utilization on floats is illustrated through an example six-unit project. Since floats can be used to accommodate uncertainty of production rates during planning and variability during execution, fewer floats (buffers) in the planning phase may more likely lead to a longer project duration in the execution phase. A probabilistic model is simulated to compare the impact of the RSM and CPM schedules on the project duration.

KEY WORDS

Repetitive scheduling, continuous resource utilization, float management, simulation

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INTRODUCTION

Repetitive activities are found commonly in the construction of multi-story buildings, pipelines, highways, and housing development projects. For such projects, similar activities are repeatedly performed from unit to unit and crews follow one another like a parade (Riley and Sanvido 1997). Projects comprising mostly repetitive activities are classified as repetitive projects.

In a traditional CPM network, an activity's float is defined to be the time span in which the completion of the activities may occur and not delay the termination of the project. When an activity possesses floats, it is a non-critical activity. By postponing the start times of non-critical activities, floats may be used to achieve different resource-oriented objectives, such as time-cost trade-off, limited resource allocation or resource leveling. Moreover, floats may also be used as "schedule buffers", which buffer downstream activities from upstream flow variation and uncertainty (Ballard and Howell 1995).

Harris and Ioannou (1998) indicated that when CPM is applied to schedule repetitive projects, the early start schedule may not be optimal because a time gap may exist between units for the same crew moving from one unit to the next. In other words, if an activity with a faster production rate than its predecessor starts as soon as possible, its crew will have to wait at the end of every unit for the predecessor crew to finish their job in the next unit. The time gap between units represents a significant amount of waste, i.e., unproductive idleness of crews. RSM was proposed to remedy this inadequacy by achieving continuous resource utilization via a pull-system scheduling approach (Yang and Ioannou 2001a).

In this paper, we demonstrate the cost-saving benefits of continuous resource utilization in the RSM schedule. The underlying assumption is that crews will be paid from when they start work in the first unit until they fully complete work in the last unit. That is, crews would be kept on site even though they cannot proceed to the next unit due to the occupation of the preceding crew. In this case, crews may slow down their work in the current unit or perform some preparation work. To keep unproductive crews on site is to avoid possible comeback delays and costs associated with the reallocation of crews and equipment.

Since the RSM schedule may possess fewer floats than the CPM early start schedule, delays on activities may more likely prolong the project duration. A probabilistic model is simulated in this paper to evaluate the effect of continuous resource utilization on the project duration. Similar simulation procedures and comparisons between the CPM and RSM schedules can be employed when project managers would like to choose between longer project duration/more work continuity of crews and shorter project duration/less work continuity of crews.

CONTINUOUS RESOURCE UTILIZATION

In repetitive projects, resources (i.e., crews and equipment) move from location to location and complete work that is prerequisite to starting work by the following resources. For example in a pipeline project, crews performing "epoxy paint coat" are scheduled to lead crews performing "pipe welding" by a specified number of pipes since epoxy paint should be applied at each welding connection. The scheduling problem posted by repetitive multi-unit projects with repeating activities is the minimization of the project duration subject to continuous resource utilization (i.e., continuous work flow) from unit to unit as well as the technical constraints between activities. Continuous work flow has been proposed as a significant goal in the Lean Construction literature (Ballard and Tommelein 1999). The problem of achieving continuous resource utilization is not directly addressed by CPM, nor by its resource-oriented extensions, such as limited resource allocation and resource leveling. In CPM, to achieve continuous resource utilization requires a complete activity-by-activity analysis and correction of the network, a process that may be cumbersome and fraught with errors.

Although the Line of Balance method (LOB) has been proposed to schedule repetitive projects since 1960s (Lumsden 1968), it requires the following restrictive assumptions: each crew has to maintain the same production rate from unit to unit; different crews have to perform their work in the same working sequence; and crews have to work in every unit. These assumptions impede the implementation of LOB.

The Repetitive Scheduling Method (RSM) was proposed to attain continuous resource utilization in repetitive projects without the restrictive assumptions required by LOB (Harris and Ioannou 1998; Yang 2002). RSM helps planners schedule crews to work continuously from one repetitive unit (e.g., house, floor, or pipe) to the next by pulling (i.e., postponing) the start time in the preceding unit so that the finish time in that unit would meet the start time in the latter one. This pulling mechanism is not provided by CPM. RSM eliminates unforced idleness, the idle time between two units when crews finish work in the preceding unit but have to wait for other preceding crews to finish prerequisite work in the latter unit. The unforced idleness is due to unbalanced production rates, uncertainty regarding the production rates during planning, and variability during execution. Since the idleness does not result from any forced causes, such as bad weather, labor accidents, or equipment breakdown, it is classified as unforced idleness. By eliminating unforced idleness in the planning phase (as opposed to the execution phase), RSM treats problems associated with undesired work interruption, such as unproductive waiting, comeback delays (Ashley 1980), and morale impact (Business Roundtable 1982).

Although continuous resource utilization may often be advantageous, work interruption may be necessary or preferred under certain conditions (Lutz 1990; Yang and Ioannou 2001a). Work interruption is necessary because of two types of technological constraints. First, an activity cannot start at the current location until its "successor" has been finished at the previous location. For example, "formwork" for the second floor slab cannot start until "concrete placement and curing" on the first floor is finished assuming one set of slab form is available. Because "concrete placement and curing" has to succeed "formwork" on every floor, it is impossible to have the formwork crew work continuously. Second, specific activities may possess no-wait constraints. Such an activity must remain stop-and-go to follow its predecessor closely. For instance, initial tunnel support must be placed immediately following the penetration of a boring machine, it is therefore infeasible to postpone the start time of placing initial support to achieve work continuity. Work interruption may be preferred when violation of continuous resource utilization leads to a shorter project duration. That is, bottleneck processes should start as soon as possible to allow the start of succeeding activities. RSM allows planners to specify arbitrary work interruption. For those activities, in which planners do not specify any work interruption, the requirement of continuous resource utilization is automatically assumed and treated.

RSM attains work continuity not only between “unit and unit” but also between “activity and activity” when the activities employ the same crew. For example in highway rehabilitation projects, common laborers may perform not only patching work for the road surface but also the installation of dowel bars in-between concrete sections. In this case, "continuity relationships" in RSM (as opposed to traditional precedence relationships in CPM) can be defined between two activities to pull the finish time of one activity to meet the start time of the other.

POSSIBLE CYCLE DUE TO THE PULLING PROCESS

A possible cycle due to the pulling process of RSM is illustrated in Figure 1. Activities A1, A2, and A3 form a continuity activity chain, i.e., there are continuity relationships between A1 and A2, and between A2 and A3. Activity B succeeds activity A1 and precedes activity A3. The start time of activity B is determined by another predecessor and the lag value between A1 and B is 2 days, and that between B and A3 is 4 days. The lag values (i.e., the difference between the early start time of the successor and the early finish time of the predecessor) between activities A1 and A3 is 5 days while that between A2 and A3 is 3 days.

To satisfy the precedence relationship between A1 and B, pulling A1 (i.e., postponing its start time to 16) would push the start time of B to 18. This would then push the start time of A3 to 24 and open up the lag between A2 and A3. The new lag of 2 days between A2 and A3 would require another pull at A1 and A2. By continuing this cycle, scheduling would never stop and fail. This cycle is therefore "unresolveable". Note that the cycle may be unintuitive when there are multiple intermediate activities. For example, if there are other intermediate activities between B and A3, the cycle may be hard to observe in a traditional CPM network. RSM, however, is able to identify the cycle.

The cycle in Figure 1 may be resolvable when the duration of B is shorter than or equal to the duration of A2, i.e., 4 days. In this case, RSM still pulls activities A1 and A2 to ensure continuous resource utilization. In contrast, if the duration of B is greater than that of A2, RSM would identify the cycle and requires users to drop either one of the continuity relationships. Detailed procedures of RSM can be found in (Yang and Ioannou 2001b).

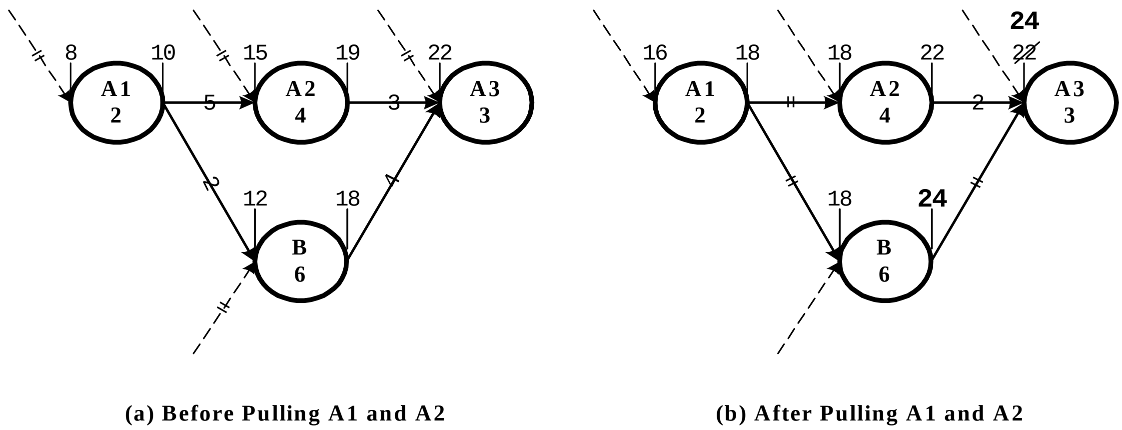

Figure 1. Work Continuity Between Activities and Possible Cycle

COST-SAVING BENEFITS OF CONTINUOUS RESOURCE UTILIZATION

In this section, we use the six-unit project described in (Harris and Ioannou 1998) to demonstrate possible cost-saving benefits of continuous resource utilization. The project involves six repetitive units, each having six discrete activities that repeat from unit to unit. Figure 2 shows the precedence network of these activities in the first unit. All the relationships are finish-to-start and each activity is performed by a specific crew. Due to a technical constraint, activity C cannot start until 2 days after activity A is finished in every unit.

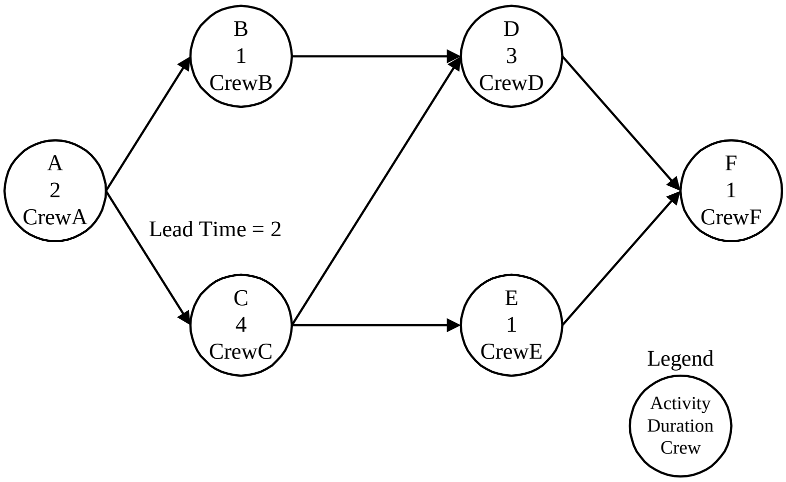

Figure 2. Precedence Network of the Six-unit Project in Unit 1

The duration of each activity in each unit is shown Table 1. The unit duration of the A activities is 2 days in units 1, 2, 5, and 6. Because the amount of work to be done in units 3 and 4 by the A activities is twice the work to be done in unit 1, the unit duration is 4 days/unit in units 3 and 4. The unit duration of the B activities is 1 day/unit. Activity B is scheduled with a work interruption of 5 days between units 3 and 4 because the subcontractor's truck can deliver material sufficient for completing only 3 units and at least 5 days are needed between deliveries. The C activities take 1 day to finish a unit but unit 5 does not require activity C. The D, E, and F activities maintain the same unit duration (3, 1, and 1, respectively) in all the units.

Table 1. Unit Duration of Activities in the Six-unit Project

Name/Dur.	**Unit 1**	**Unit 2**	**Unit 3**	**Unit 4**	**Unit 5**	**Unit 6**
A	2	2	4	4	2	2
B	1	1	1	1	1	1
C	4	4	4	4	0	4
D	3	3	3	3	3	3
E	1	1	1	1	1	1
F	1	1	1	1	1	1

For the purpose of this example, assume that every activity is subcontracted out and the daily direct cost of each activity is $5,000. Since the project manager is concerned about comeback delay, he decides to pay subcontractors in full even when the crews are idle to keep them on the site. This project is scheduled in CPM and the resulting bar chart is shown in Figure 3 with the dark bars representing the critical activities. The project duration is 30 days. In contrast to the bar chart, a CPM network composed of 35 activities (6 activities in 6 units while unit 5 does not need activity C) is difficult to present here. This illustrates a major disadvantage of using CPM network to schedule repetitive projects. Every activity is broken down into work for all six units except activity C. A1 represents activity A in unit 1; B1 represents activity B in unit 1, and so forth.

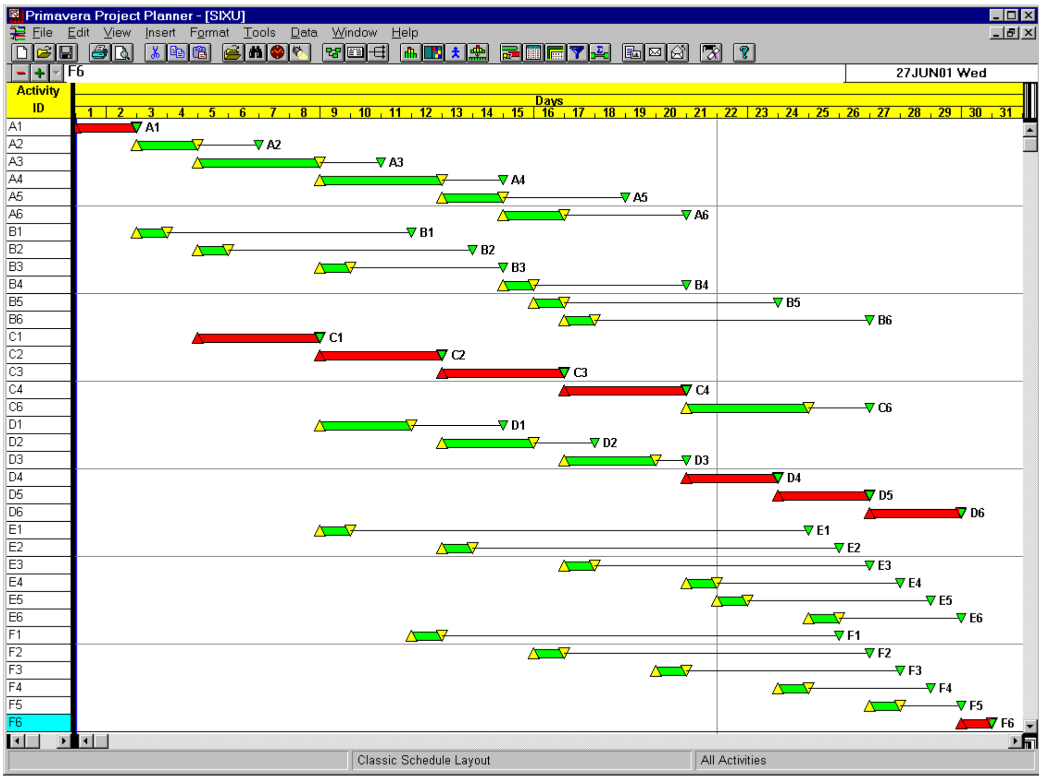

Figure 2. CPM Early Schedule for the Six-unit Project

The early start and finish times of each activity are tabularized in Table 2. The overall direct cost based on the CPM early schedule is $515,0000. This assumes that crews have to be paid from when they arrive to the site until their work is fully complete including idle days if any.

Table 2. Direct Cost of the Six-unit Project based on the CPM Early Schedule

NAME	**START TIME** (end of day)	**FINISH TIME** (end of day)	**PAID DAYS**	**DIRECT COST ($)**
A	0	16	16	80,000
B	2	17	10*	50,000
C	4	24	20	100,000
D	8	29	21	105,000
E	8	25	17	85,000
F	11	30	19	95,000

*: Excludes 5 days of the pre-scheduled work interruption 103 (days) $515,000

The six-unit project is then scheduled by RP2 (a computer program implementing RSM). RP2 automatically pulls activities to achieve continuous resource utilization. The resulting RSM graphical schedule is shown in Figure 3 while the attributes of each activity are listed in Table 3. The project duration remains intact (30 days). Both the heavy and dotted portions of production lines represent critical activities that if delayed, would delay the project. The dotted portions are called "resource critical"; they are critical because of the requirement of continuous resource utilization. In other words, the resource critical activities can actually start earlier if continuous resource utilization is not needed.

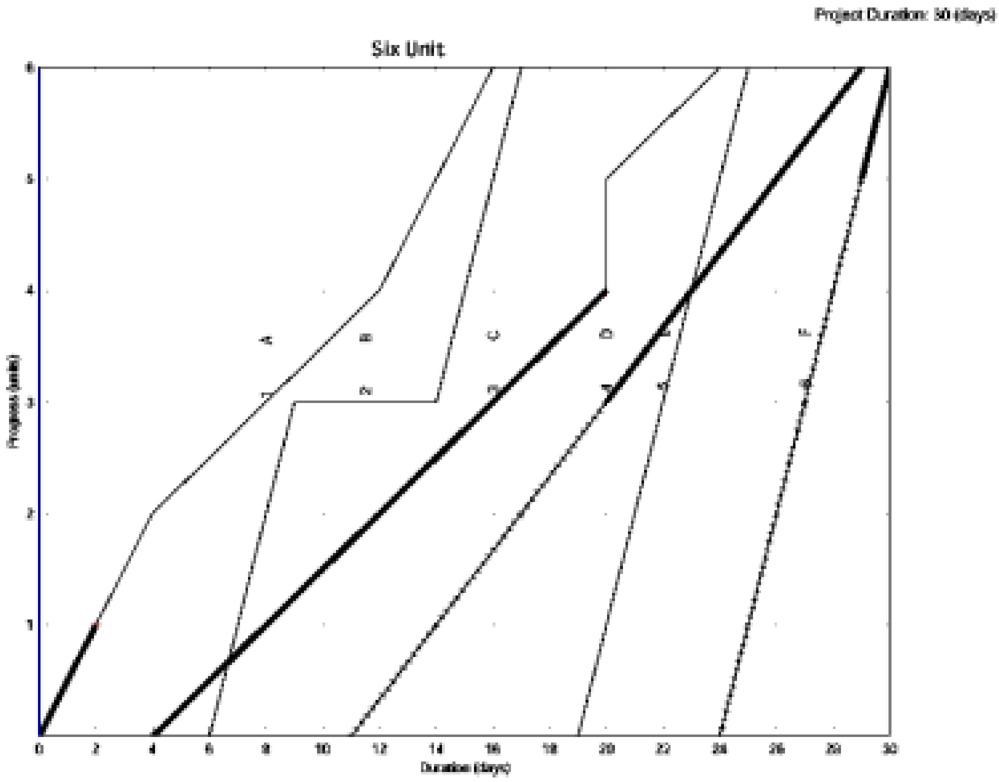

Figure 3. RSM Graphical Schedule for the Six-unit Project

Table 3 Direct Cost of the Six-unit Project based on the RSM Schedule

NAME	**START TIME** (end of day)	**FINISH TIME** (end of day)	**PAID DAYS**	**DIRECT COST ($)**
A	0	16	16	80,000
B	6	17	6*	30,000
C	4	24	20	100,000
D	11	29	18	90,000
E	19	25	6	30,000
F	24	30	6	30,000

*: Excludes 5 days of the pre-scheduled work interruption 72 (days) $360,000

According to the start and finish time recorded above, the total number of paid days is 72 (the sum of paid-days), which results in the overall cost of $360,000. By comparing direct costs associated with the CPM early schedule and the RSM schedule, the cost-saving benefits of continuous resource utilization are (515,000-360,000) / 515,0000 = 30% of the overall direct cost. This portion of cost-saving benefits have not yet taken into account the non-quantifiable value of continuous resource utilization, such as avoiding come-back delays, lower morale and productivity owing to work discontinuity.

It is not new to postpone the start of an activity to achieve continuous work flow. Seasoned project managers estimate the necessary postponement when they suspect the occurrence of work discontinuity. This manual process, however, can be a time-consuming and error prone exercise when the size and complexity of a project increase.

DECREASES IN AVAILABLE FLOATS FOR CONTINUOUS RESOURCE UTILIZATION

RSM postpones the starts of activities to achieve uninterrupted resource usage. A trade-off exists in this mechanism; the RSM schedule ensures continuous resource utilization, but it may decrease the time buffers (floats) by which an activity can be delayed without delaying the completion of the project. In the six-unit project, the sum of total floats in the CPM early schedule equals 152 days while that in the RSM schedule decreases to 75 days (the sum of column e in Table 4). This demonstrates that the RSM schedule possesses fewer floats than the CPM early schedule. The calculations are tabularized in Table 4. In Table 4, the floats of activity segments D1, D2, D3, and F1-F5 are reduced to zero while that of activity segments B1, B2 and E1-E5 are decreased but not zero. In other words, some activities become critical (e.g., activities D1, D2, and D3) or more critical (e.g., activities B1 and B2) because the amount of time that activities can be delayed without delaying the project is decreased. The shaded rows indicate the activities whose total floats are decreased.

STOCHASTIC ANALYSIS ON PROJECT DURATION

Despite the cost-saving benefit resulting from continuous resource utilization, it is often of practical concerns that decreasing floats may more likely cause a longer project duration when some activities are delayed during the execution phase of the project. That is, more activities become critical (e.g., resource critical activities in Figure 3). If any of these activities is delayed when the project is in progress, the project tends to be delayed.

In this section, we perform a stochastic analysis to compare the CPM early and late schedules and RSM schedules for the six-unit project. The three sets of activity start times are compared in a simulation model that is programmed in STROBOSCOPE (Martinez 1996). The random variants are activity durations and the statistic output, i.e., the performance measure, is to estimate the expected project durations for all three schedules.

The underlying distribution of unit durations is a normal function. The mean is listed in Table 1 while the standard deviation is set to be 40% of the mean. For instance, the duration of activity A1 follows a normal distribution with the mean of 2 days and the standard deviation of 0.8 days. The standard deviation is used to accommodate the variation of production rates and uncertainty associated with activity duration. Notice that the duration must be positive even though the normal distribution may yield negative random numbers for activity duration, which is unreasonable. Furthermore, the duration is set to be continuously distributed whereas in practice, paid days of crews are often counted as discrete numbers in accordance with the preference of project managers (i.e., either half a day or a full day).

Table 4. Comparison of Total Floats Between CPM and RSM Schedules (Six-unit Project)

	(a)	(b)	(c)	(d)=(c)-(a)	(e)=(c)-(b)
	CPM	**RSM**	**CPM**	**CPM**	**RSM**
Act.	**Early Start**	**Start**	**Late Start**	**Total Float**	**Total Float**
A1	0	0	0	0	0
A2	2	2	4	2	2
A3	4	4	6	2	2
A4	8	8	10	2	2
A5	12	12	16	4	4
A6	14	14	18	4	4
B1	2	6	10	8	4
B2	4	7	12	8	5
B3	8	8	13	5	5
B4	14	14	19	5	5
B5	15	15	22	7	7
B6	16	16	25	9	9
C1	4	4	4	0	0
C2	8	8	8	0	0
C3	12	12	12	0	0
C4	16	16	16	0	0
C6	20	20	22	2	2
D1	8	11	11	3	0
D2	12	14	14	2	0
D3	16	17	17	1	0
D4	20	20	20	0	0
D5	23	23	23	0	0
D6	26	26	26	0	0
E1	8	19	23	15	4
E2	12	20	24	12	4
E3	16	21	25	9	4
E4	20	22	26	6	4
E5	21	23	27	6	4
E6	24	24	28	4	4
F1	11	24	24	13	0
F2	15	25	25	10	0
F3	19	26	26	7	0
F4	23	27	27	4	0
F5	26	28	28	2	0
F6	29	29	29	0	0
			Sum:	**152**	**75**

The simulation model is composed of two sets of Queues and one set of Combis. The first set of Queues holds crews and exists between units. The waiting time in Queues represents the idleness of crews from unit to unit. The second set of Queues holds dummy resources ("precedence") and exist between activities. This is to ensure the finish-to-start precedence relationships between activities. Each of the Combis denotes an activity segment (e.g., A1 or B2). In STROBOSCOPE, a Combi represents a task that starts when certain conditions are met. The conditions in the simulation model are two-fold. First, the precedence relationships preceding the Combi are met. Second, the crew performing the Combi has been released from the preceding unit.

STROBOSCOPE provides a convenient Semaphore statement, which is always associated with a Combi. The Semaphore statement is used to evaluate external logic expressions to start a Combi. When the result returns TRUE, the Combi can start. Otherwise, STROBOSCOPE would abort the attempt to instantiate the Combi. The logic expression here controls the planned start time of activities in the first unit according to the CPM late and RSM schedules. For example, based on the RSM schedule, the Semaphore statement of Combi B1 would be "SimTime>=6". This is to ensure that activity B1 cannot start unless the simulation time is later than Day 6, which is the planned start time of B1 in the RSM schedule.

A single run of simulation would be insufficient to yield any significant conclusion. Here the replication of the model is performed for 500 times. Besides, to compare the RSM and CPM schedules, we must synchronize the random numbers across all three systems on any particular replication. Hence, the "seed" and "streams" (where the random numbers are picked) for variants in all three systems are chosen to be the same.

The sample mean and standard deviation for the project duration are tabularized in Table 5. Since the number of replication is large, the sample mean approximates the expected project duration. An approximate 100(1-)% (0< <1) confidence interval for the project duration can be calculated as follows (Law and Kelton 1991).

$$\overline{\mathrm{X}}(\mathrm{n}) \pm t_{\mathrm{n}-1,\alpha/2}\frac{\mathrm{S(n)}}{\sqrt{n}} \quad (1)$$

where $\overline{\mathrm{X}}(\mathrm{n})$ denotes the sample mean; $\mathrm{S(n)}$ denotes the sample standard deviation; and n represents the number of replications. The 95% confidence intervals of the project duration are shown in Table 5.

Table 5. Simulation Result for the Project Duration (Six-unit Project)

n=500	Sample Means $\overline{\mathrm{X}}(\mathrm{n})$	Sample Standard Deviation S(n)	95% Confidence Interval
CPM Early Schedule	32.12 (days)	3.099 (days)	32.12 ± 0.273 (days)
CPM Late Schedule	33.79 (days)	2.565 (days)	33.79 ± 0.268 (days)
RSM Schedule	33.28 (days)	2.419 (days)	33.28 ± 0.213 (days)

To demonstrate the cost-saving benefits of the RSM schedule, we also collect the paid days of crews during simulation. The paid days are counted when the crew starts work in the first unit until it complete the last unit. The simulation results are shown in Table 6.

Table 5 indicates that although the project duration of the RSM schedule is estimated slightly greater than that of the CPM early schedule, the expected difference is at most [(33.28+0.213)-(32.12-0.273)] ≈ 1.6 days. The CPM late schedule, which starts every activity at the latest possible time, yields the largest expected project duration (33.79 days). It is important to recognize that a longer project duration may lead to higher indirect costs (e.g., operating the site office or applying safety program), which increase with time.

Table 6 shows that the paid days of crews based on the RSM schedule is significantly less ([105.39-80.63] ≈ 25 days) than that based on the CPM early schedule. The decrease in paid days represents the cost-saving benefits. The difference in paid days is not significant (less than 1 day) between the RSM and CPM late schedules. Recall that the assumption here is that the project manager is willing to pay the crews from when they arrive to the site until their work is fully complete including idle days if any.

Table 6. Simulation Result for the Paid Days of Crews (Six-unit Project)

n=500	Sample Means $\overline{X}(n)$	Sample Standard Deviation S(n)	95% Confidence Interval
CPM Early Schedule	105.39 (days)	12.500 (days)	105.386 $\pm$ 1.098 (days)
CPM Late Schedule	80.63 (days)	9.469 (days)	80.63 $\pm$ 0.832 (days)
RSM Schedule	80.06 (days)	10.269 (days)	80.06 $\pm$ 0.903 (days)

Harris (1978) indicated that there are many cases where a longer project duration is acceptable if the overall cost can be lowered. In our analysis above, the RSM schedule leads to a much less direct cost (because of fewer idleness days) than the CPM early schedule with a slightly longer project duration. The CPM late schedule, in comparison, yields a larger expected project duration and a slightly larger expected paid days than the RSM schedule. Hence, the project manager of the six-unit project may prefer the RSM schedule to the CPM early/late schedules.

Note that the conclusion above does not suggest that the RSM schedule is always more beneficial than the CPM early/late schedules. Instead, it suggests that the simulation procedures discussed in this section can be used to evaluate the effect of continuous resource utilization on the overall project duration. The trade-off problem is between a higher cost caused by the idleness and a possible shorter project duration.

CONCLUSIONS

This research follows a previous attempt (Yang and Ioannou 2001a) in achieving continuous resource utilization. The primary purpose is to demonstrate possible cost-saving benefits of continuous resource utilization and to present a simulation analysis in investigating the effect of continuous resource utilization on the project duration. The analysis provides promising evidence for further implementation.

RSM reduces floats of activities (i.e., the time that activities can be delayed without delaying the project) to achieve the continuous usage of resource. Historically, project managers used early start times of activities, even if they may be inefficient. Part of the reason is the lack of confidence in handling uncertainty associated with actual construction, such as the requirement of getting crews/materials in right place at right time. By postponing the start times of some activities, non-critical activities may become critical or more critical. This increases project managers' dependence on suppliers, subcontractors, and labor, etc. A further study on eliminating variability in production (Howell and Ballard 1998) and implementing lean thinking on supply chain management, performance management, and coordination among trades will be advantageous to attain continuous resource utilization in practice.

A six-unit project is used to illustrate the implementation of RSM in the following practical situations:

- Crews may skip units.
- Subcontractors may need break time between units for material delivery
- Crews may have varied production rates from unit to unit
- Activities may have multiple predecessors and successors.

Further sensitivity analyses in the present simulation model would be beneficial. For example, the variability of activity duration may play an important role in determining the confidence interval of the project duration. Hence, different levels of variability can be modeled by the magnitude of the standard deviation (e.g., 10%, 20%, 30%, etc.) Moreover, it may be more practical to count the paid days of crews as discrete integers as opposed to continuous real numbers.

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