Priority rules and relationships in micro-scheduling of construction wood-framing tasks

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This paper presents the application of the activity precedence diagram method to determine the most effective distribution of crew size and work-flow for framing. The duration of each micro-activity (task), such as lumber handling, measuring and marking, cutting, placing, or nailing was measured directly from a video-taped activity while the task precedence was determined using elementary geometrical and technological reasoning. Scheduling software was used to calculate the sequencing of tasks and the total duration of the activity for varying crew sizes. Additionally, several resource leveling principles were applied for each crew size. The results show a quick convergence towards the minimum possible total production time and, also, allow selection of an optimal crew size for a given activity. Furthermore, the results show that the productivity of two to three person crews can be increased by applying different task selection criteria as suggested by various resource leveling principles.

Key Words: framing, micro-activity, scheduling software, resource leveling

Introduction

The use of planning and scheduling (P&S) software has been common practice in construction for about three decades. (Liberatore & Johnson & Smith, 2001). As the use of P&S software has concentrated on solving problems at the whole project level, the level of detail of the activities is normally lower (i.e. more detailed) than the equivalent of level 5 in the CSI work breakdown structure (WBS) (CSI Master Format, 2004). From the point of view of task distribution and execution at the crew level, CSI level 5 is a "macro" level.

While crew sizes and task sequencing is usually done at the foreman's level, P&S principles can be used to determine the most effective size of a crew and the best way of distributing the work among crew members. The purpose of the research presented here is to develop clearly communicable collaboration principles that can be implemented by any crew and not to have the construction crews distribute the work by running P&S software. Well-organized crews probably use the same collaboration principles intuitively, but it was too difficult to capture those principles. (Mitropoulos & Cupido, 2009). The detailed application of P&S principles in a project will be called micro-scheduling in this paper. The study presented here applies to carpenters (framers) involved in the production of interior wall wood frames in residential and non-residential buildings.

Background and Problem Statement

Research in P&S has focused on optimization at the higher (activity) level of operations. Newer algorithms, such as The Sequence Step Algorithm (Srisuwanrat, 2009), deal with minimizing the duration of repetitive projects with probabilistic activity durations, while achieving continuous resource utilization. This has applicability at the activity level in macro-scheduling of construction projects. Other authors (Kastor & Sirakoulis, 2009) were concerned with PERT/CPM network techniques that are based on the assumption that all needed resources will be available. The scarcity of resources is usually a reason for project delays. Project Management software packages were studied to see how resource conflicts are resolved by using resource leveling. Their work evaluates the effectiveness of resource leveling tools of three popular packages by comparing the results when leveling two real construction projects as case studies. There are also misconceptions identified by other researchers about project scheduling and time related to resource constraints (Herroelen & Leus, 2005). The misconceptions relate to the role of the critical path, the critical sequence (critical chain), active schedules, and the insertion of buffers in the baseline schedule as a protective mechanism against schedule distortions during project execution. The possible errors revealed by their research are illustrated using example schedules developed for an illustrative project.

Shortcomings in existing methods, for the identification of critical tasks in resource-constrained projects in situations involving more than one unit of renewable resource, are highlighted through examples of research done by Rivera & Duran (2004). The concepts of critical set and critical cloud are proposed in their paper as an extension to the concept of critical task. The researchers allow a consistent and unified treatment of criticality in projects with resource constraints, and provide an unambiguous procedure to establish the critical sequence and its constituents. An algorithm to determine "critical sets" and "critical clouds" is proposed and applied to a sample project.

While these algorithms are useful for optimizing whole projects, field personnel and crafts people need simpler principles to optimize the productivity of their crews. The study presented in this paper compares resource leveling algorithms and priorities for P&S programs to determine if simpler task priority principles (i.e. what should be done next if there is an available choice of tasks) can be deducted from those algorithms. The research considers the limitation of resources (number of carpenters) and the pool of available tasks required to be accomplished for completing wood frames for interior walls. The process of assigning tasks to the resources (framers), their descriptions, and codification of the tasks is shown in the next section. To put it simply, the problem statement can be reduced to the following question: how do we decide who does what and when, in an effective crew?

Objectives

This study focused on the suitability of commercial project management programs like Primavera (P5) and Microsoft Project (MSP) for micro-scheduling the framers' tasks when building wall frames, as well as the effectiveness of these software packages to enhance the optimum team composition and task allotment (i.e. who does what and when). Specifically, the following three goals were sought:

1. Determine the program best suited for micro-scheduling (when selecting between MSP and P5) and the recommended settings for these programs.
2. Test the influence of various resource leveling principles on the total productivity of the framing crew.
3. Test the feasibility of task automation sequencing and determine the needs for further research.

Methodology

The building of a wood frame structure was videotaped and analyzed frame-by-frame. The structure was built by two framers. The specific tasks performed (such as handling, marking, and cutting) and the duration of each task (in seconds) was recorded. The tasks were then generalized to allow application of general principles to instances of specific elements or assemblies. For instance, the task "cutting" can be applied to any of the studs in the frame. Cutting is preceded by both measuring and marking or by aligning (with another element).

However, task precedence is only one of the three types of constraints taken into account. The constraints to the tasks are: 1) Precedence constraints; 2) Resource availability constraints for specific tasks; 3) Resource continuity constraints for specific tasks. While precedence constraints specify the technological order of work, resource availability and continuity constraints control the utilization of resources in the framing activity. To obtain a practical and efficient schedule, the three types of constraints presented above must be accounted for in micro-project scheduling. In practice, a precedent network was created for all of the framers' tasks. Because the support of the P&S programs is geared towards macro-scheduling, the time was altered by considering each second as one day in the schedule. Each individual task was then assigned the resource of one framer and the duration was measured from the recording. The precedent network was then run on each P&S program, with each of the available resource leveling options. This battery of calculations was performed with increasing resource limits until the total duration of the activity (building the frame) stabilized at an absolute minimum value (i.e. adding more framers would not reduce the total time of building the frame). The results were recorded and analyzed.

Case study

The wood frame shown in figure 1 was built by two framers. Figure 1 shows the as-built of the frame with all the elements in place, including nails.

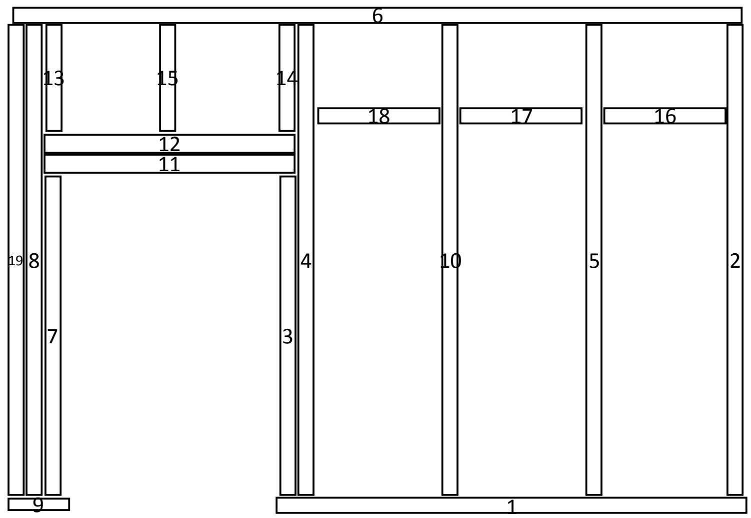

Figure 1. Interior wall – a wood frame built on-site by carpenters

A generic notation was developed for the implementation of the tasks for micro-level scheduling. Each element was identified by a two-digit code (01, 02…. 19) and each nail was identified by the codes of the elements it connects. Seven types of tasks were identified, as described below. The names were selected so they can be identified by their initial only.

- **H**andle (element XX or stud XX).
- **T**ape measure (element XX or stud XX).
- **I**n-field measure (or In-situ measure of element XX).
- **M**ark XX_YY(ZZ) (mark element YY or ZZ on element XX).
- **C**ut (element XX or stud XX).
- **P**lace (element XX or stud XX).
- **N**ail (side & toe nailing) XX_YY (nail element XX to element YY – the head of the nail is in element XX).

Therefore, all actions assigned to the available studs will represent all tasks available for execution. For example, the available tasks pertaining to element 6 for one labor resource are as follows: H 06, T 06, C 06, P 06, M 06 05, M 06 10, M 06 13, M 06 14, M 06 15, M 06 34, M 06 78, N 06 02, N 06 34, N 06 05, N 06 78, N 06 10, N 06 14, N 06 15 and N 06 19. It is noted that elements 3 and 4, as well as 7 and 8 form two sub-assemblies; therefore, they are considered in the related tasks together after nailing them as pairs. These tasks were entered in Microsoft Project and Primavera P5 software for the purpose of scheduling and resource leveling. The duration of each task was recorded and introduced in both programs. A total of 120 tasks were identified, including both tasks of starting and finishing the frame (lifting and placing in a determined location). Each task requires that one resource (one carpenter) be assigned to it.

The duration of each task, such as lumber handling, measuring and marking, cutting, placing, and nailing was measured directly from the video-taped activity for each instance. In other words, if C 15 took 3 seconds and C 18 took 2 seconds, each was introduced with their own duration.

Task precedence was determined using elementary geometrical and logical reasoning. Specifically, the rules used consisted of the following precedence chain for any element: Handle, Measure & Mark, Cut, Nail, or Place. Note that Nail and Place are both successors of Cut. There are some situations when two elements are nailed together even if they are not yet in their final place. An example is E 03 and E 04 that are nailed together to form element 34. The possibility of generating other subassemblies (i.e. other than E 34 and E 78) was not considered in this study. The study focused on improving the efficiency of the current construction method only. Furthermore, any nail that is covered by an element (such as N 11 03 covered by 12), will precede the placement of the covering element. In the notation introduced here: N 11 03 → P 12. Using these rules the precedence table can be created semi-automatically. An excerpt of the precedence table is reproduced in table 1.

Table 1

Predecessors for elements 11 and 12

Element	TASKS	Predecessors
E 11	H 11	S
	T 11	H 11
	C 11	T 11
	M 04 11	H 04
	M 08 11	H 08
	P 11	C 11, M 04 11, M 08 11
E 12	H 12	S
	T 12	H 12
	C 12	T 12
	P 12	C 12, P 11, N 11 34

Note that the placing of element 11 and element 12 (i.e. P 11 and P 12) have respectively different types of precedent tasks. As stated before, these precedents have been determined from geometric and technological conditions. Special rules were considered and were incorporated for the two existing subassemblies, specifically pertaining to elements 3, 4 and 7, 8. (shown in table 2):

Table 2

Predecessors rules for element 3-4 and 7-8

Element	TASKS	Predecessors Rules
E 34	M 01 34	H 01
	M 06 34	H 06
	P 34	N 03 04, M 01 34, M 06 34
E 78	M 09 78	H 09
	M 06 78	H 06
	P 78	N 07 08, M 09 78, M 06 78

Microsoft Project and Primavera in micro-scheduling of wood-framing tasks

A comparison was made between MSP and P5 to select which of the two programs is best suited for micro-level P&S. As expected, the results of unconstrained scheduling were identical – a common critical path indicated that they share a common algorithm. However, a final analysis of both programs concluded that P5 is better suited for micro-projects, as it gives more options in regard to priority rules when applying resource leveling. The main disadvantage of P5 is the difficulty in linking to externally generated data.

Execution of Resource leveling in the scheduling software

When leveling resources, both MSP and P5 use priority, rule-based algorithms to generate workable schedules. The priorities come into play when two or more activities/tasks compete for the same resource, at the same time. P5 allows the user to select the preferred priority from a list of predetermined options. Some of these priority options are Activity ID, Activity Priority, Early Finish (EF), Early Start (ES), Free Float (FF), Late Finish (LF), Late Start (LS), Total Float (TF), etc. There are other classified priority rules such as Original Duration, by Department, by Phase, by Planned Finished or Planned Start, remaining Duration, and by Responsibility. These additional priorities were deemed irrelevant for the purpose of micro-scheduling. MSP provides fewer choices for selecting the leveling priorities to determine which task to delay or split first: Standard, ID only, or Priority and Standard. Their meanings are described below:

- Standard leveling order - in this case Project examines: Predecessor dependencies, Slack time, Dates, Constraints, and Priorities. MSP will honor predecessor relationships first so that the leveling solution will not have tasks that violate their relationships. Then, among tasks that have similar relationships, tasks with higher slack will be moved before those with lower slack values. Task dates, priorities, and constraints will be taken into account, in that order. This method is the default and is the one that is most commonly chosen for leveling.
- Leveling by ID - Using ID Only, MSP will delay tasks with higher task ID values first before looking at lower task IDs. Thus, tasks listed at the top of the page automatically have a higher priority in the leveling algorithm than tasks at the bottom of the page.
- Leveling by Priority and Standard - MSP first examines any set task, summary task, or project, and then examines the standard factors. Using this method, the task priority is the primary driver factor to determine how Project will delay your tasks. With this method, tasks with lower priorities are leveled first, and tasks with the same priority will be delayed based on the other criteria. This method gives you control over how Project will make its leveling decisions.

MSP also has three options in regard to the leveling possibilities, specifically:

- Level only within available slack (the leveling will only happen within the existing time scale and will not put the completion date back).
- Leveling can adjust individual assignments on a task.
- Leveling can create splits in remaining work.

For the purpose of this study, these options were not taken into account when priorities were run for results. The reason for ignoring these options was to not alter the final results when strictly applying priority rules or leveling orders. However, it is recommended as future research to study the results with these leveling possibilities applied individually to priority rules or leveling orders.

Results

Using each of the two programs (MSP and P5), the total production time was computed for a matrix of scenarios. The matrix of scenarios contains the maximum number of available framers (resource limitation – starting from one and going up to fifteen framers for both software) and each of the resource leveling principles deemed applicable, as mentioned in the previous section. Table 3 presents the results of one resource-leveling principle, in one of the programs. The productivity of the framers in a crew was calculated as the fraction of the standard time obtained with only one framer available. For instance, referring to table 3, the productivity of the 3 framers crew was calculated as follows: Total duration of building the frame was 137s. Total labor-seconds for the 3 framers is 137s x 3 = 411s. The total labor seconds when resources are fully employed (i.e. one framer): 384s. The difference, 411s – 384s = 27s, is deemed to be idle time distributed among the crew members. Productivity of the crew was calculated as 1 – 27s / 384s = 93%. It is worth noting that using the resource leveling principle presented in table 3, the total time stabilizes at 76s, with a crew of 11 framers. Increasing the crew size above this limit will only reduce the productivity, but will not decrease the total production time. The CPM column shows the critical path obtained with running of the respective resources. In the case of the 3 framers, critical path obtained after leveling was pertained to tasks of element 6 and assembly 78. The duration column shows the percentage of the duration obtained after resource leveling relative to the absolute total duration when one resource is used (384 s). While the calculations do not take into account the synergies of the crew, they provide a consistent base for comparing the resource-leveling principles with one another. The points of interest are discussed below.

Table 3

Duration and productivity in MSP

Nr	Priority rule	Total duration	Resources units	Nr. People	CPM	Equiv. Time	Prod. Frame	Duration
1	**Standard**	384	100%	1	E19	384	100%	100%
		194	200%	2	E19	388	99%	51%
		137	300%	3	E6+E78	411	93%	36%
		116	400%	4	E6+E78	464	83%	30%
		104	500%	5	E6+E78	520	74%	27%
		96	600%	6	E6+E78	576	67%	25%
		90	700%	7	E6+E78	630	61%	23%
		85	800%	8	E6+E78	680	56%	22%
		81	900%	9	E6+E78	729	53%	21%
		78	1000%	10	E6+E78	780	49%	20%
		76	1100%	11	E6+E78	836	46%	20%
		76	1200%	12	E6+E78	912	42%	20%

The results of the calculations are shown in figure 2. It is evident that the greatest benefit is obtained when moving from a one to two framer crew. A crew of three framers still has some benefits (i.e. project crushing). Increasing the crew to more than three framers offers no significant benefits. This conclusion, specific to the frame presented in figure 1, was consistent for all leveling principles, both in MSP and in P5. As mentioned above, there were eight different priority rules applied to resource-leveling in P5. The results for the productivity and total duration are presented in figures 3 and 4, respectively. These results show that the productivity of two to three person crews (i.e. total duration of the framing) depends significantly upon the resource-leveling principle.

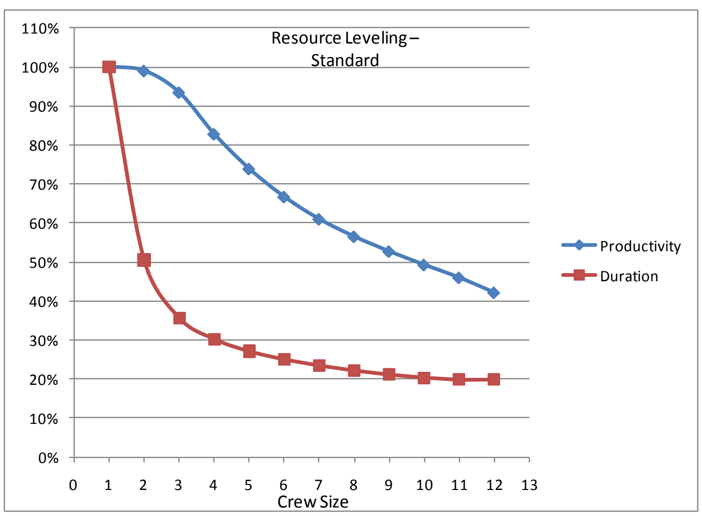

Figure 2. Productivity and duration with variation of crew size (MSP)

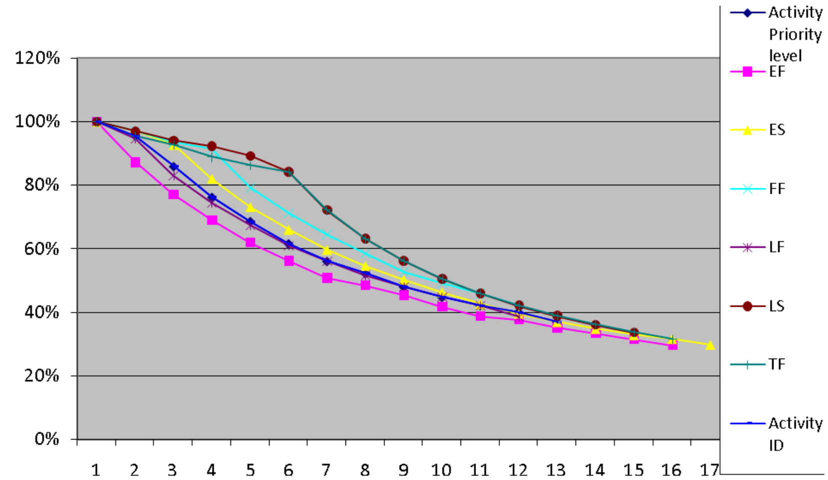

Figure 3. Productivity comparison for different leveling priority rules in P5

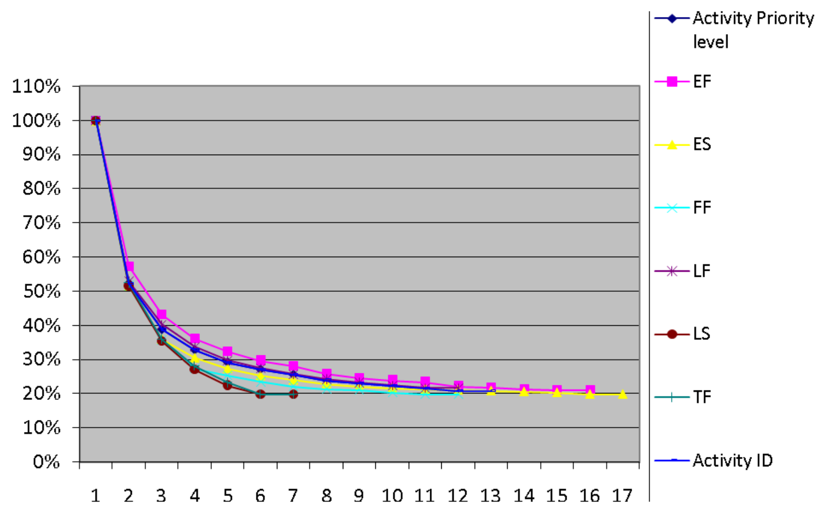

Figure 4. Duration comparison for different leveling priority rules in P5

For instance, looking at the case of three framers on the graph in figure 3, one can notice that productivity varies between 77% when the EF priority rule was applied and 94% when the LS priority rule was applied. This means that, when faced with several choices of the next possible task, the framers' decision will influence the total productivity of the crew. A wrong decision will generate idle time downstream in the process. In the case above, the productivity improvement from EF priority to LS priority is 22% (17% increase related to the base of 77% is 22%).

The following is the detail of the framers' activities in the two extreme cases.
<u>Case 1</u>: EARLY FINISH rule
Framer 1 can execute the following first eight tasks: H 05→H 12→H17→H 04→H 13→T 09→H 01→T 15
Framer 2 can execute the following first eight tasks: H 09→H 03→H15→H 02→H 11→T 03→T 13→M 05 16
Framer 3 can execute the following first eight tasks: H 14→H 05→H16→T 14→H 07→T 03→T 09→H 01
<u>Case 2</u>: LATE START rule
Framer 1 can execute the following first eight tasks: H 06→T 06→C 06→P 09→H 04→H 03→T 03→C 03
Framer 2 can execute the following first eight tasks: H 07→T 07→C 07→P 07→P 08→N 07 08→H 01→H 03
Framer 3 can execute the following first eight tasks: H 08→H 09→T 09→C 09→M 09 78→M 06 78→P 78→N 09 78
It is noticeable that a more organized and logical sequence was obtained when the late start rule was applied for the activity (all tasks) in P5.

Discussion

As stated in the introduction, the goals of this study were threefold:

1. Determine the program best suited for micro-scheduling (when selecting between MSP and P5) and the recommended settings for these programs.
2. Test the influence of various resource leveling principles on the total productivity of the framing crew.
3. Test the feasibility of automation of task sequencing and determine the needs for further research.

This section presents the conclusions and discussion for each goal:

1. P5 was found to be better-suited for micro-scheduling when compared to MSP. The only reason for this finding is the availability of more leveling preferences in P5. The data input and data exchange with external programs was found to be more convenient in MSP. The input of tasks and their numbering in P5 was found difficult to work with, but was essential in application of the resource leveling rules.
2. Resource leveling principles play a significant role on crew productivity. For a team of three framers, the Late Start leveling priority resulted in a 22% productivity increase compared to Early Finish leveling priority. This means that, when presented with a choice of tasks, the framers should choose the one with the earliest late start. More research is needed to formulate this statement in a way that is easily understood and implemented by framers.
3. The application of the micro-scheduling of tasks to various trades is universal. However, there are two conditions that must be satisfied when using the scheduling software. These two conditions refer to a clear description of the work (good definition of the tasks) and a geometrical reasoning, along with a technological reasoning assigned for relationships between tasks. Each of these topics requires further research. Identifying the task before the activity is performed requires a definition of tasks taxonomies for various construction methods. A report about task taxonomies is in preparation. The methodology of the study is implementable at a larger scale not just to construction trades. The optimization of the wood-framing tasks can be applied in any activities that can be described through a fair taxonomic work breakdown.

For the framing activity presented in this paper, the tasks were completely identified and defined by watching the video-capture of the real activity. Most of the precedence rules were generated automatically, using elementary formulas in Excel. Corrections were made manually to accommodate for exceptions. This exercise provided a good validation to the idea that full automation of micro-scheduling is possible and worth pursuing

References:

Herroelen,W. & Leus, R. (2005). Identification and illumination of popular misconceptions about project scheduling and time buffering in a resource-constrained environment. *Journal of the Operational Research Society*, *56*, 102-109

Kastor A. & Sirakoulis K. (2009). The effectiveness of resource leveling tools for resource constraint project scheduling problem. *International Journal of Project Management*, 27, 493 – 500.

Liberatore, M. J. & Johnson, B. P. & Smith, C. A. (2001). Project Management in Construction: Software use and research direction. *Journal of Construction Engineering and Management*, *127*(2), 101 - 107.

MASTERFORMAT 2004 EDITION, NUMBERS & TITLES. *The Construction Specifications Institute* [WWW document]. URL http://www.csinet.org/s_csi/sec.asp?TRACKID=&CID=1377&DID=11339

Mitropoulos, P. & Cupido, G. (2009). Safety as an Emergent Property: Investigation into the Work Practices of High-Reliability Framing Crews. *Journal of Construction Engineering and Management*, *135*(5), 407 - 415.

Rivera, F. & Duran A. (2004). Critical clouds and critical sets in resource-constrained projects. *International Journal of Project Management*, 22, 489 – 497.

Srisuwanrat, C. (2009). *The Sequence Step Algorithm-A simulation-based scheduling algorithm for repetitive projects with probabilistic activity durations.* Doctoral Dissertation, University of Michigan, USA.