PROJECT MANAGEMENT UNDER UNCERTAINTY: SOLUTION METHODS REVISITED

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ABSTRACT

Project Management involves onetime endeavors that demand for getting it right the first time. On the other hand, project scheduling, being one of the most modeled project management process stages, still faces a wide gap from theory to practice. Demanding computational models and their consequent call for simplification, divert the implementation of such models in project management tools from the actual day to day project management process. Special focus is being made to the robustness of the generated project schedules facing the omnipresence of uncertainty. An "easy" way out is to add, more or less cleverly calculated, time buffers that always result in project duration increase and correspondingly, an increase in its cost. A better approach to deal with uncertainty seems to be to explore slack that might be present in a given project schedule especially when a non-optimal schedule is used. The combination of such approach to recent advances in modeling resource allocation and scheduling techniques to cope with the increasing flexibility in resources, as can be expressed in "Flexible Resource Constraint Project Scheduling Problem" (FRCPSP) formulations, should be a promising line of research to generate more adequate project management tools. In reality this approach is frequently used by project managers in an ad-hoc way.

INTRODUCTION

All definitions of a Project (PMI 2013) commonly agree that it is a onetime endeavor aiming to reach a predefined goal or more generally, a set of goals. Consequently it is imperative that the project team and, more particularly the project manager, have not only the necessary skills but also the best tools to help them getting it right the first time.

On the other hand, project managers and their teams face increasing challenges as projects become more complex (due to, for example, increasing technological evolution, multidisciplinary and globalization) along with increasing competiveness (again globalization generally plays a crucial role here) often implies a well-defined and committed a priori cost and delivery date. In this scenario, project managers face, right from the start, the challenge to balance the scope-time-cost project triangle where time and cost "cannot" deviate from the agreed upon values but the scope embraces/encompasses a whole set of uncertainties. A typical scenario for the project execution is that of assigning a set of resources available during the project duration. While this approach seems quite comfortable for the project manager it leaves no space for coping with uncertainties especially when the project plan is established as an optimal or near optimal schedule which is the correct option if one wants to be at its best competitive form. This is one of the reasons that lead to budget overruns and delays that occur in the majority of large projects (Couto and Teixeira, 2007; Flyvbjerg et al., 2003).

So, uncertainty resulting from several origins like not fully understood technical challenges and/or requirements leading to misestimating the necessary work to be done, along with resource unforeseen unavailability (Elmaghraby, 2005) collides many times with the demand to deliver on time and with no additional costs.

How then are projects managed in such typical scenarios? Many times (Jia et al., 2007; Olsen and Swenson, 2011), the method at hand is to use the available resources to work more within the same time unit (typically a day) either by considering this extra work as overtime (in which case there will be additional costs) or not. The latter case is typically managed in an ad-hoc empirical way.

These are the issues that will be further studied in the remaining of this document and a research line will be identified that enable the development of a prototype for further supporting project managers to cope with these increasing demands.

THE PROBLEM

The question is then how can a project manager develop and control a plan that is cost effective and is simultaneously able to cope with uncertainties?

Within this scope, project costs are assumed to be a non-decreasing function of its duration and thus the project plan needs to be based on an optimal or near optimal makespan schedule. The project makespan will be the considered parameter to be minimized.

The question will be divided in order to firstly identify its importance and secondly to assure such a plan can cope with uncertainty:

- What is the impact in the project duration (and thus in its cost) regarding the scheduling tool and/or technique used?
- How can an optimal or near optimal schedule be produced?

The focus of this document is to address the first question.

LITERATURE REVIEW

In spite of these techniques, recent examples of projects with budget overruns and delays well beyond their promised delivery dates are countless, due to several reasons not the least important of which is poor planning and control (Couto and Teixeira, 2007; Couto, 2012). In spite of some slight improvement in the last years, the Standish Group's report (The Standish Group, 2009) shows a disturbing projects success rate, with 32% of all projects succeeding, 44% being late, over budget, and/or with less than the required features and functions and 24% failing (cancelled or never used). More recent reports (The Standish Group, 2014) show that this problem is not solved. Complex projects are normally performed in dynamic environments characterized by uncertainty and risk (Schatteman et al., 2008). It is believed that the use of specific models designed to address these concerns would contribute to a more efficient use of the resources while keeping the risk controlled, particularly in large and complex projects, enabling an increase in project success rates.

Two aspects stand out as crucial to the successful adherence to budgetary and time constraints: the proper allocation of the resources and the explicit recognition of the stochastic nature of the undertakings.

The optimization of resource allocation in projects, considering stochastic work contents was first addressed by Tereso in 2002 (Tereso, 2002). Two models were developed, one using Dynamic Programming (DP) (Tereso et al., 2006, 2004) and the other using the Electromagnetism like Mechanism (EM) (Birbil and Fang, 2003; Tereso et al., 2009). Next an Evolutionary Algorithm was used (Tereso et al., 2007) with better results than the DP model but similar to the EM model. This problem was also studied considering multiple resources (Tereso et al., 2008). The resource complementarity problem (Silva et al., 2011, 2010) and the multimode problem (Santos and Tereso, 2011) were also addressed. In this line of work, a model was proposed by Elmaghraby and Morgan (2007) using a combination of Geometric Programming (GP) methodology with Sample Path Optimization (SPO). The authors aimed to extend the applicability of "resource allocation in activity networks under stochastic conditions" to large activity networks, i.e., projects.

Classical models assumed that each activity has a deterministic duration and known resource requirements, and attempted to “optimally” schedule the activities, in whichever sense optimality was defined. This gave rise to the well-known Resource-Constrained Project Scheduling Problem (Demeulemeester and Herroelen, 2002) or RCPSP. The majority of these studies suffer from the serious flaw of ignoring the uncertainty present in real life projects. Unfortunately, the inclusion of uncertainty in these models seemed to meet with insurmountable obstacles. Initial attempts to overcome these obstacles used more or less complex probability distributions to model time uncertainties, assuming averages (or other single value probability representation) to be the values to use in traditional models (PERT falls into this category). This approach proved to be insufficient to model real world projects (Elmaghraby, 2005).

Therefore, researchers had to deal with random variables and had to increase the estimate of the time of realization of certain “key events” by an allowance (or “buffer”) that would absorb delays in case some activities took longer than estimated, and thus achieve a higher degree of robustness of the resulting schedules in what is sometimes referred as the stability makespan trade-off. The most simplistic way to achieve this is to right shift non started activities where makespan is sacrificed on behalf of the project schedule stability.

A more complex approach to deal with time uncertainty is to use a multi stage decision process known as Stochastic RCPSP (SRCPSP) (Stork, 2001). This process does not rely on a predefined baseline schedule with all inconvenient that this implies, like not having a way to discuss the schedule a priori (before project starts) with the project's stakeholders (allowing external project interfacing activities to be managed), just to mention one aspect that is crucial to any project manager. It rather relies on scheduling activities as the project progresses, selecting precedence and resource feasible activities to be started at some decision points using scheduling strategies (or policies). Time uncertainty is expressed in SRCPSP by considering activity durations as random variables (except for dummy ones).

Another approach to deal with uncertainty and to produce robust project schedules is to use a combination of proactive and reactive project scheduling techniques (Demeulemeester and Herroelen, 2009). This approach involves a proactive and a reactive phase. In the proactive phase, a baseline schedule is constructed typically by some RCPSP method. Based on the baseline schedule, robust resource allocation is performed and time buffers are inserted. Robust resource allocation basically consists in establishing a resource flow (transferral of resources between activities) that minimizes the possibility that a potential resource failure propagates throughout the project's schedule. Time buffers are inserted in order to accommodate eventual activity delays, taking into consideration uncertainties and anticipated disruptions.

Several strategies and algorithms were proposed to maximize the schedule stability or the schedule robustness, minimizing the project's makespan or the project's cost. While some aim for optimality, others will settle for "good enough solutions". One should mention two alternative methodologies that can be a basis for these algorithms: the railway scheduling and the roadrunner scheduling (Van de Vonder et al., 2005). Railway scheduling always starts activities at their scheduled start time or later while the roadrunner approach will always start activities as soon as possible. The first favors schedule stability (don't start earlier than scheduled because that unnecessarily messes with the schedule) while the latter is defensive regarding the project's makespan (don´t miss the opportunity to gain some additional slack time). Tian and Demeulemeester (2010) argued that the roadrunner methodology does not reduce the project's expected makespan.

In the reactive phase, reactive scheduling procedures are used to correct the schedule (Van de Vonder et al., 2006) if later unforeseen disruptions occur during the actual project execution. Reactive procedures are applied during project execution, reacting at project's disruptions. This can be regarded as a disruption management multi-stage decision process. Effective reactive procedures are just emerging and to cope with their complexity some procedures deal specifically with time uncertainties or resource uncertainties (single mode procedures). While some work is already being done for combined and more complex disruptions, there are certainly research opportunities to be explored here.

Related to this line of research, one should refer the Critical Chain Project Management (CCPM) method (Goldratt, 1997), derived from the Theory of Constraints (TOC), which is a well-known and a widely used method with a tool (ProChain) that facilitates its practical use by project managers. CCPM simplifies the uncertainty problem by focusing in the Critical Chain (CC) that is the longest chain (path) of activities that are precedent and resource dependent in the schedule, i.e., that defines the project's duration. This chain is to be protected in disregard of the others, even if they are marginally not selected as CC. Time buffers are concentrated into Feeding Buffers (FB) and Project Buffers (PB). Simplistic FB are inserted whenever a non CC activity meets the CC, protecting the CC from delays coming from that chain. PB are inserted immediately before the last (dummy) activity in order to protect the project's due date. Time buffers (FB and PB) are usually set at 50% of the duration of the chain they are inserted to (note that the project makespan is determined by the overall duration of the CC). This 50% buffer size rule does seem baggy and should take into account other resource, activity and project characteristics. CCPM also uses Resource Buffers (RB) that mainly serve as a warning system and are inserted when an activity in the CC uses a different resource from the previous activity. It also relies on Buffer Management (BM) to act as a proactive warning mechanism and uses the roadrunner scheduling methodology.

Several authors, e.g. Herroelen and Leus (2004), criticize the feasibility orientation of CCPM in disregard to optimality which can be critical in highly competitive markets (as are globalised markets) especially regarding large projects.

As is explained, there are a lot of possibilities to be explored within these two lines of work. Their mix, that is, a combination of the resource allocation problem considering stochastic work contents and multimodal activities with the proactive/reactive techniques, being the driver of this research, will be certainly a challenging one. Nevertheless the belief that this combination is possible and that it will enable a better project management tool will make this challenge worthwhile.

METHODOLOGY

To assess the impact of the scheduling model in the resources allocated to a project, the following parameters will be used:

Scheduling problem: RCPSP

Test projects: psplib J30 (Kolisch and Sprecher, 1997) instances of RCPSP

Solution methods:

- To obtain optimal solutions: Demeulemeester and Herroelen (1997, 1992) branch and bound algorithms.
- To represent an heuristic method: SSGS (Serial Scheduling Generation Scheme) with the following typical priority rules (Kolisch, 1996):
  - LJN (Lowest Job Number);
  - RND (Random);
  - SPT (Shortest Processing Time);
  - LPT (Longest Processing Time);
  - MIS (Most Immediate Successors);
  - MTS (Most Total Successors);
  - LNRJ (Least Number of Related Jobs);
  - GRPW (Greatest Rank Positional Weight);
  - EST (Earliest Start Time);
  - EFT (Earliest Finish Time);
  - LST (Latest Start Time);
  - LFT (Latest Finish Time);
  - MSLK (Minimum Slack);
  - GRWC (Greatest Resource Work Content);
  - GCRWC (Greatest Cumulative Resource Work Content).
- To include one of the most popular project management software: MSProject (Microsoft Project 2013).

All solution methods, besides MSProject, were coded in MSVC++ 2012 (C++ of Microsoft Visual Studio 2012).

In order to achieve typical values for MSProject scheduling and respect RCPSP definition, the following parameters were set (all other parameters remain at their default values):

- "Saturday" and "Sunday" were set to "working time" with the same working hours as the other days (this was done for easier Gant chart visualization and comparison);

- "Leveling Options" were set in order not to allow activity split.

Then, scheduling each psplib J30 instance within MSProject was performed by the following procedure:

- Import activity data (activity name, their precedence relations and their required resources) into MSProject;
- Import resources data (resource name and availability) into MSProject;
- Set "Task Mode" to "Automatic Schedule" for all activities;
- Execute the procedure "Level All".

All durations (project instances and their activities) were considered as days.

It is possible to improve MSProject generated schedules using its embedded scheduling algorithms and some additional VBA (Visual Basic for Applications) (Trautmann and Baumann 2010).

Although possible, this is not typically used and therefore, was not considered.

RESULTS

In figure 1, a graphical view for all 480 psplib J30 instances is shown. The xx axis represents each instance and the yy axis the correspondent project duration (t). To enhance the deviation from the optimal values, durations are displayed having the negative part as the project optimal duration and the positive part as the deviation from the optimal. Accordingly, the values for the solution methods are represented as:

- A bar for the optimal ("Opt") duration, with the finish time corresponding to t=0 and the absolute negative start time corresponding to the project optimal duration;
- A red dot (dots are connected with a red line) for the MSProject project ("MSP") duration with the positive part representing the deviation from optimal value. The overall project duration is then the sum of this value to the correspondent optimal one;
- A vertical line for all priority rules SSGS durations. The upper limit of each vertical line (bounded with a small horizontal line) represents the maximal deviation from optimal of all durations computed with each priority rule and the lower limit represents the minimal one. Again, the overall project duration is the sum of these values to the correspondent optimal one.

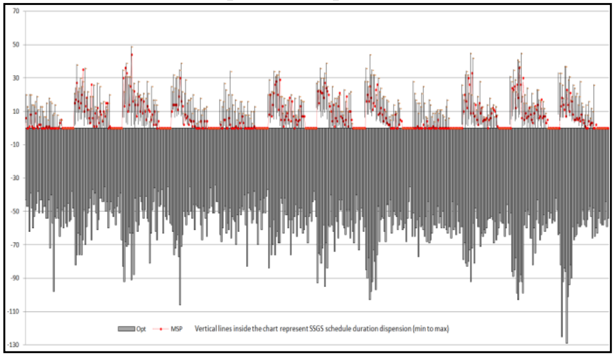

Figure 1: Project duration for all 480 J30 instances

In Table 1, a summary of all 480 psplib J30 instances regarding their scheduled durations are presented. Again, the optimal duration (d_opt) of each instance (i) is used as reference to emphasize the potential for improvement. Values are shown as absolute deviations from optimal, for each other solution method, regarding:

- "Max", given by: $\max_{\mathrm{i}}(\mathrm{d_i} - \mathrm{d_{opt}})$;
- "Average", given by: $\frac{\sum_{\mathrm{i}}(\mathrm{d_i} - \mathrm{d_{opt}})}{480}$;
- "Min", given by: $\min_{\mathrm{i}}(\mathrm{d_i} - \mathrm{d_{opt}})$.

Corresponding relative deviations are also considered which are calculated by replacing $(d_i - d_{opt})$ in the previous formulas by $(\frac{d_i - d_{opt}}{d_{opt}})$.

Table 1: J30 project duration summary

Optimal duration is used as reference	Optimal duration	Deviation from optimal duration															
		SSGS with defined priority rule															MSProject
		LJN	RND	SPT	LPT	MIS	MTS	LNRJ	GRPW	EST	EFT	LST	LFT	MSLK	GRWC	GCRWC	
Max	129	37	45	49	39	36	26	34	36	31	37	30	30	39	39	35	44
Average	59	5,96	7,83	10,55	7,71	6,11	4,22	6,71	6,50	5,74	7,25	3,31	3,67	6,12	7,39	6,72	6,13
Min	34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Max (%)		44%	63%	57%	51%	48%	32%	49%	52%	44%	46%	33%	34%	49%	60%	57%	53%
Average (%)		9%	13%	17%	12%	10%	7%	11%	10%	9%	12%	5%	6%	9%	12%	11%	9%
Min (%)		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Based on the results presented above, the resources that must be available for each project can be calculated. The average values for all instances are presented in Table 2 for each resource type k and considering:

- the optimal solution;
- the best schedule resulting from SSGS (from all enumerated priority rules);
- the MSProject schedule.

The required resources (that is the total work content of the project), which are independent from the schedule, and the percentage of unused resources are also presented.

Table 2: J30 average resources

	Required ($\sum d_i r_{ik}$)				Available ($a_k d_i$)				% Unused ($\frac{\text{Available} - \text{Required}}{\text{Available}}$)			
	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4
Optimal	570,66	583,46	574,56	581,99	1160,78	1171,60	1161,13	1161,61	52,00%	51,50%	51,96%	50,78%
Best SSGS	570,66	583,46	574,56	581,99	1191,42	1202,88	1192,46	1192,24	53,54%	53,05%	53,48%	52,36%
MSProject	570,66	583,46	574,56	581,99	1263,46	1276,71	1265,40	1264,40	56,42%	55,97%	56,40%	55,27%

CONCLUSIONS AND FURTHER RESEARCH

In the majority of projects, costs can be modeled as this type of optimization problem (minimize the project duration) and therefore will have a non decreasing cost function of its duration. As the presented results show, the scheduling solution method will greatly influence the project's cost and, the most common scheduling techniques used, present poor results even considering small projects (less than one hundred activities) like the problem instances used in this analysis.

Additional efforts to develop and make available tools with better scheduling techniques are increasingly necessary. These tools should provide schedule durations closer to optimal and should be more deterministic (independence of the problem instance) in achieving them, both in the per se (as presented in this study) and regarding the time needed to compute them (not covered in this study).

But, even using these non-optimal schedules, projects do, more than often, overrun their estimated duration and costs. This means that additional efforts are needed to, given a better or worst schedule, in the duration sense, make it more resistant to failure, i.e., make it more robust. Several techniques were studied to achieve these goals, starting with PERT (Program Evaluation and Review Technique) where simplistic project duration estimations, beyond deterministic ones, are calculated, to increasingly enhanced versions of RCPSP. As mentioned before, some of these enhancements are:

- SRCPSP (Stochastic RCPSP) whose lack of a base schedule hinders its use (see Ballestin and Leus (2009) as an example);
- MRCPSP (Multi-mode RCPSP) (see Peteghem and Vanhoucke (2010) as an example);
- Proactive/Reactive Scheduling (see Demeulemeester and Herroelen (2009)).

These techniques are still being subject of additional research as is a recent topic designated as FRCPSP (Flexible-resources RCPSP) (see Naber and Kolisch (2014) as an example) which can be seen as a generalization of MRCPSP.

This study is a starting point to the development of a tool to address the problem of transforming a given schedule into a more robust one attempting to attain a better behavior when unscheduled events occur during project execution.

Further Research

This study is a starting point to the development of a tool to address the problem of transforming a given schedule into a more robust one in the sense that the new one will behave better when unscheduled events occur during project execution. The aim is to provide the project manager a tool that helps him to determine a schedule and to assist him in making the best decisions that lead to minimum deviation in the original schedule duration when uncertainties arise and, in this way, keep the project’s costs. Schedule robustness will be enhanced by combining the concepts of Flexible Resources and Proactive/Reactive scheduling. The idea is to, given a schedule S^b (baseline schedule), obtained by any of the scheduling techniques considered above or any other, redistribute resources in order to accelerate critical activities at the expense of slowing down non-critical activities. This can be achieved without changing the given schedule S^b (keeping activity start times) if resources are "flexible" in the sense that their "per unit of time" (typically a day) work capacity can vary from below to above of their predefined nominal value (a_k^{nom}). This can be represented by the following expression: $a_k^{nom}(1-\alpha_k^-) \leq a_k \leq a_k^{nom}(1+\alpha_k^+)$, where a_k is the effective resource availability, α_k^-/α_k^+ is the maximal decrease/increase of resource k availability per time unit. The a_k variable can be continuous ($a_k \in \mathbb{R}$) or can be a (more realistic) fraction discrete variable ($a_k \in$ {discrete set}$\subset \mathbb{Q}$). As an example one might have a_k^{nom}=1 corresponding to 8h per day and $\alpha_k^- = \alpha_k^+ = 25\%$ leading to an effective resource availability of $0.75 \leq a_k \leq 1.25$ or, expressed in hours, $6 \leq a_k \leq 10$. In an extreme case where only integral working hours per day are allowed $a_k \in \{6,7,8,9,10\}$ or, expressed in days, $a_k \in \{0.75, 0.875, 1, 1.125, 1.25\}$. The model could then slow down activities with slack by using its resources in a reduced availability mode so that critical activities (activities with slack) can be executed at a faster rate by using its resources at an increased availabiltity mode.

Critical activities will have then a time buffer that can be used to cope with eventual increases in their work content to avoid them to delay the project. This new working schedule S^w is better suited to face project uncertainties and in this sense is more robust than the original one.

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