Robust Project Scheduling

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Abstract

The majority of publications in the extensive literature on resource-constrained project scheduling focus on a static deterministic setting for which a so-called baseline schedule is computed prior to project execution. In the real world, however, a project may be subject to considerable uncertainty. During the actual execution of a project, the baseline schedule may indeed suffer from disruptive events causing the actually realized activity start times to deviate from the predicted start times that were given in the baseline. This text focuses on robust project scheduling, in particular the development of effective and efficient proactive and reactive scheduling procedures. Proactive scheduling aims at generating robust baseline schedules that carry sufficient protection against possible schedule disruptions that may occur during project execution. Reactive scheduling procedures aim at repairing the baseline schedule when the built-in protection fails during the execution of the project. We discuss the fundamentals of state of the art proactive/reactive project scheduling approaches and, along the lines, discuss key directions for future research.

Contents

1

Introduction

Scheduling and sequencing is concerned with the optimal allocation of scarce resources to activities over time. More in particular, the *project scheduling problem* involves the scheduling of project activities subject to precedence and/or resource constraints. This scheduling process results in a so-called *baseline schedule*, which lists for each project activity, a planned starting and finishing time. The baseline schedule serves very important functions [6, 116]. A major function is to allocate resources to the different project activities to optimize some measure of performance. If developed as a feasible finite capacity schedule, there exists at least one capacity-feasible resource allocation for the work planned and the baseline schedule allows one to identify peak and low capacity requirement periods. The baseline schedule also serves as a basis for planning external activities, such as material procurement and committing to shipping due dates to customers. Such visibility of future actions is of crucial importance within the inbound and outbound supply chain. Especially in multi-project environments, one needs to determine before the start of the project a schedule that is in accord with all parties involved, be it clients and suppliers, workers and other resources. It may be necessary to agree on a time window for work to be done by subcontractors and to organize the resources to best support a smooth schedule execution. Current communication technology such as the Internet allows companies to share their project schedules with their subcontractors and suppliers on a continuous basis, with the expectation that the subcontractors and suppliers will use this information to provide just-in-time deliveries. Reliable baseline schedules enable organizations to estimate the completion times of their projects and take corrective action when needed. They allow for scheduling and resource allocation decisions that in turn should allow quoting competitive and reliable due dates [75].

The project scheduling problem has been the subject of extensive research since the late 1950s leading to an impressive amount of literature. Recent project scheduling textbooks include Demeulemeester and Herroelen [46], Dorndorf [48], Klastorin [89], Klein [90], Neumann et al. [124], and Schwindt [145]. Review articles have been published by Brucker et al. [19], Hartmann and Briskorn [65], Herroelen et al. [71], Kolisch and Padman [96], Özdamar and Ulusoy [127], and Weglarz et al. [168]. Over the years, a wide variety of commercialized project management software packages have been released and put to use in practical project settings [34, 94, 114, 154, 155]. Despite all these efforts, many publications have documented projects that went wildly over budget or dragged on long past their originally scheduled completion date [17, 51, 52].

Ensuring project success, delivering projects on time, within budget and according to specifications, still seems to be notoriously difficult. Often, the root cause for many of these failures can be traced back to ineffective project planning and scheduling [39, 69]. Who is to blame?

First, it cannot be denied that the popular project management literature and professional project management organizations seem to adhere rather little importance to the resource-constrained project scheduling issue. The majority of popular project management textbooks and project planning sections in operations management textbooks leave some room for the discussion of *temporal scheduling* (the computation of the earliest and latest start times and slack values of the project activities using the common critical path method (CPM) and/or PERT (Project Evaluation and Review Technique) [86, 113]), but do not excel in dwelling deeply on the resource scheduling issue.

In doing so, they leave the impression that it is not that important which methodology is used to generate precedence and resource feasible baseline schedules. Some authors go very far in their denial of project scheduling importance. Goldratt [57, p. 217] argues that project scheduling procedures do not matter at all because "in each case the impact on the lead time of the project is very small."

As a result, it does not come as a surprise to find that in practice, project management teams generate project baseline schedules, often using commercially available project planning software, using the simple critical path methodology, focusing on the notion of the critical path as the longest path in the project network. The baseline schedule reflects the planned activity start times computed as the result of a longest path computation that solely relies on the planned duration of the project activities and their mutual sequence dependence as determined by the precedence relations expressed in the project network. Surveys conducted among companies operating in various industrial sectors [33, 39]) reveal that (a) information systems for project planning are mainly used for communication and representation, rather than for optimization, and (b) that software users have limited knowledge of the software tool they are using and of project planning and control in general.

Second, the majority of the extensive research literature on resource-constrained project scheduling (see Herroelen [69]) focuses on a *deterministic* setting, where activity durations, resource requirements and resource availabilities are known with certainty and where the problem reduces to the development of a workable baseline schedule that satisfies both the precedence and resource constraints and that is "optimized" for a single scheduling objective (most often the project duration). During execution, however, a project is subject to considerable uncertainty, which may lead to numerous schedule disruptions. This uncertainty stems from a number of possible sources: activities may take more or less time than originally estimated, resources may become unavailable, material supplies may arrive behind schedule, ready times and due dates may have to be modified, new activities may have to be incorporated or activities may have to be abandoned due to changes in the project scope, etc.

Recently, the recognition that uncertainty lies at the heart of project planning induced a number of renewed research efforts in the field of project scheduling under uncertainty. The major objective of this publication is to review the fundamentals of robust project scheduling through the deployment of proactive/reactive project scheduling procedures.

Proactive/reactive project scheduling procedures try to cope with schedule disruptions that may occur during project execution using a three-stage process: (a) the generation of a precedence and resource feasible baseline schedule, (b) protecting the baseline schedule against disruptions that may occur during project execution, and (c) deploying a reactive scheduling procedure to repair the baseline schedule during project execution when needed.

We will elaborate on the three-stage scheduling process in the subsequent six sections of this text.

The generation of a feasible baseline schedule is covered in Sections 2 and 3. It is still common practice in many industries that companies and contractors rely on the critical path calculations applied in CPM or PERT to generate the baseline schedule for a project [69]. In doing so, the baseline schedule is commonly generated using commercially available project planning software packages. The baseline schedule reflects predicted activity start times that are computed through a straightforward critical path analysis that solely relies on the planned deterministic or expected durations of the project activities as well as their mutual sequence dependence as determined by the precedence relations expressed in the project network.

Temporal scheduling, the generation of precedence feasible (early and late start) schedules using CPM or PERT is discussed in Section 2. As indicated in the CPM and PERT entries in Table 1.1, this type of temporal scheduling does not take into account existing resource constraints and the temporal schedules are commonly generated without any built-in protection against disruptions that may be caused by anticipated risk factors [32, 33, 39, 69, 77, 76, 72].

Section 3 focuses on the *resource management* issue (the RCPSP entry in Table 1.1) and the state of the art in generating baseline schedules that are not only precedence but also resource feasible. We introduce the fundamental deterministic resource-constrained project scheduling problem (RCPSP) that lies at the heart of the resource leveling procedures applied by commercial project planning software. We elaborate on the basics of the heuristic approaches that are commonly deployed in practice for its solution.

In Section 4, we focus on *project scheduling under uncertainty*. We discuss two major types of uncertainties that can be identified, assessed, and managed properly: time uncertainties and resource uncertainties. Coping with these types of known unknowns will be the major concern in this text. We first introduce the basics of stochastic project scheduling (the SRCPSP entry in Table 1.1). Stochastic project scheduling suffers from the major drawback that no fixed baseline schedule is generated in advance of project execution. Scheduling decisions are dynamically taken using so-called scheduling policies. The proactive procedures discussed in the next two sections do not share this drawback in that they try to protect a baseline schedule against time and resource uncertainty.

Procedures for *protecting baseline schedules against time uncertainty* are dealt with in Section 5. We introduce the main schedule robustness measures used in this text and analyze two approaches for improving the stability of the feasible input schedule: robust resource allocation and time buffer insertion.

Robust resource allocation (the "robust resource allocation" entry in Table 1.1) boils down to the generation of a so-called resource flow network, which describes the way in which the individual renewable resource units are transferred between the activities in a baseline schedule. Our analysis will focus on the description of one of the most workable resource allocation procedures, known under the acronym MABO (myopic activity-based optimization).

Time buffering implies the insertion of time buffers at well-chosen locations in the schedule in an effort to prevent as much as possible the propagation of disruptions throughout the schedule. We review the logic of the popular commercially available critical chain scheduling method (the "quality robustness: critical chain" entry in Table 1.1) and reveal the need for more advanced proactive scheduling approaches (the "solution robustness: exact and suboptimal procedures" entry in

Table 1.1. Project scheduling methods.

			Proactive		Reactive			
					Single mode		Multi-mode	
	Deterministic	Stochastic Time uncertainty	Time uncertainty	Resource uncertainty	Time uncertainty	Resource uncertainty	General disruption types	Time/ resource disruptions
Ignores resources	CPM	PERT						
Considers resources	RCPSP	SRCPSP	Robust resource allocation	No advance information	WET	Exact procedure	Hybrid MIP/CP	Dedicated procedures
			Quality robustness: critical chain	Advance uncertainty information	Sampling	Heuristics		
			Solution robustness: exact and suboptimal procedures					

Table 1.1) that do exploit the uncertainty information made available by a well-taken schedule risk analysis. We provide sufficient room for describing the logic of the *starting time criticality heuristic* as a representative of an inherently simple and practically applicable time buffer insertion procedure. Critical chain scheduling assumes that activities are started as soon as possible (roadrunner scheduling) while the other discussed buffering procedures assume railway scheduling, i.e., never starting activities earlier than their planned starting time in the baseline. We discuss the results of a computational experiment set up to determine which procedure has the best performance. We conclude the section with a description of an integrated proactive scheduling procedure that combines the good things of stochastic and proactive project scheduling.

Proactive project scheduling under *renewable resource uncertainty* is covered in Section 6. We distinguish between procedures that use surrogate stability objective functions without relying on available uncertainty information (the "no advance information" entry in Table 1.1) and procedures that exploit historical information regarding either potential sources of uncertainty or the probability distributions describing the possible outcomes for each source of uncertainty (the "advance uncertainty information" entry in Table 1.1). We explore the use of so-called resource slack through the insertion of resource buffers and describe a convenient way to translate resource availability uncertainty into activity duration uncertainty. We conclude the section by describing the logic of a tabu search buffer insertion procedure.

Section 7 will be devoted to a discussion of *reactive scheduling procedures* that can be launched when the baseline schedule, despite its built-in protection, breaks and needs to be repaired. We focus on reactive scheduling in single activity mode environments where the project activities can only be executed in a single execution mode (the "single mode" column in Table 1.1) and reactive scheduling in situations where multiple possible execution modes can be identified for the project activities (the "multi-mode" column in Table 1.1). For the single-mode case, we distinguish between procedures dealing with time uncertainty (the "WET" and "sampling" entries in Table 1.1) and procedures dealing with resource uncertainty (the "exact procedure" and "heuristics" entries in Table 1.1). For the multi-mode case, we discuss an approach dealing with multiple disruption types (the hybrid mixed-integer programming/constraint programming approach indicated in the "hybrid MIP/CP" entry in Table 1.1) and conclude with a description of a number of exact and suboptimal procedures for both activity duration and resource disruptions (the "dedicated procedures" entry in Table 1.1).

Section 8 revisits the material discussed in previous sections, reviews our major findings, and identifies some future research areas.

The audience we aim at in this text can be described as the "informed newcomer." Material currently dispersed over numerous research publications is brought together within a unified comprehensive framework. Recent research findings that were not yet covered in previously published survey articles [70, 75, 76] are discussed in sufficient depth. This should not only allow the reader to grasp the state of the art in proactive/reactive project scheduling, but also reveal potential new directions for fruitful research.

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