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A hierarchical approach to multi-project planning under uncertainty

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Abstract

We survey several viewpoints on the management of the planning complexity of multi-project organisations under uncertainty. A positioning framework is proposed to distinguish between different types of project-driven organisations, which is meant to aid project management in the choice between the various existing planning approaches. We discuss the current state of the art of hierarchical planning approaches both for traditional manufacturing and for project environments. We introduce a generic hierarchical project planning and control framework that serves to position planning methods for multi-project planning under uncertainty. We discuss multiple techniques for dealing with the uncertainty inherent to the different hierarchical stages in a multi-project organisation. In the last part of this paper we discuss two cases from practice and we relate these practical cases to the positioning framework that is put forward in the paper.

(Keywords: project management; multi-project organisations; hierarchical models; uncertainty)

1 Introduction

In this paper we aim at providing an integrated approach to multi-project planning under uncertainty, which deals with both the complexity aspects of the problem and the uncertainty. Our goal is to provide a general guide for using advanced multi-project planning techniques in practice. We propose a *positioning* framework to

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distinguish between different types of project-driven organisations. This framework is based on the dimensions of *variability* and *complexity* of the organisation. The positioning framework enables the selection of appropriate multi-project management methods as a function of the organisational characteristics. We also propose a detailed *hierarchical* framework for project planning and control, which distinguishes four hierarchical levels. We discuss each level of the hierarchy with its associated project planning and control methods in detail, focussing especially on the two dimensions of the positioning framework, i.e. *complexity* and *variability*.

Project management is a management discipline that is receiving a continuously growing amount of attention; comprehensive references are Kerzner (1998) and Meredith and Mantel (2003). Both in production and in service sectors, ever more organisations and companies adhere to project-based organisation and work, within a wide variety of applications: research and development, software development, construction, public infrastructure, process re-engineering, maintenance operations, or complex machinery. A *project* can be informally defined as a unique undertaking, consisting of a complex set of precedence-related activities that have to be executed using diverse and mostly limited company resources. Project management deals with the selection and initiation of projects, as well as with their operation, planning and control.

A significant number of international high-profile projects fail to be delivered on time and on budget (The Standish Group, 1994; Winch, 1996). One example that immediately springs to mind is the construction of the Channel Tunnel, but undoubtedly, most readers can also think back on smaller-scale projects closer to their work environment, that did not work out as anticipated. A number of undesirable characteristics are associated with failing projects: budget overruns, compromised project specifications, and missed milestones. In other words, the

three basic dimensions of project success, namely *time*, *cost* and *quality*, are often in jeopardy. In order to avoid these problems, proper *project planning* is in order: a description of the objectives and general approach of the project, its resources and personnel, evaluation methods, and also a *project schedule* as well as a description of potential problems that may be encountered.

Traditionally, research has focused on planning for so-called *single-project* organisations. An increasing amount of companies, however, tend towards an organisational structure in which multiple projects are run simultaneously. A number of authors (Levy and Globerson (1997), Lova et al. (2000), Payne (1995)), explicitly point out that companies mostly run a number of projects in parallel, which share the same scarce resources, resulting in frequent conflicts of interest when more than one project require the same resource at the same time. In this paper we refer to the overall coordination of such multi-project organisations as *multi-project management*. A high degree of *complexity* and *uncertainty* about the activities and operations of the projects characterizes these environments.

As coherently described in Silver et al. (1998), Anthony (1965) proposes that managerial activities fall into three broad categories, whose names have been somewhat changed over the years to become *strategic planning*, *tactical planning* and *operational control*. These categories are concerned with different types of decisions and objectives, managerial levels, time horizons and planning frequencies, and also with different modelling assumptions and levels of detail. In order to deal with the *planning complexity* in multi-project organisations, the planning process is broken down into more manageable parts using a model for *hierarchical planning and control* based on the three managerial decision levels discerned in the foregoing.

Uncertainties in the multi-project-driven organisation are mainly caused by two sources. On the one hand, detailed information about the required activities

becomes available only gradually, and on the other hand there are a number of operational uncertainties on the shop floor. Since *all* real-life projects are faced with uncertainty, this text pays particular attention to planning models that account for *variability* and uncertain events.

We can distinguish between two distinct approaches for dealing with uncertainty, namely the *proactive* and the *reactive* approach. The proactive method tries to alleviate the consequences of uncertainties prior to the start of the project, e.g. by allocating the slack or flexibility in a plan to the periods where there are uncertainties. The reactive approach aims at generating the best possible reaction to a disturbance that cannot be absorbed by the plan without changing it. This can be done by, e.g., a replanning approach, which re-optimises or repairs the complete plan after an unexpected event occurs. Reactive approaches are particularly useful if disturbances cannot be completely foreseen or when they have too much impact to be absorbed by the slack in a plan.

De Boer (1998) points out that in many organisations, part of the work is made up by projects, while the rest is performed in 'traditional manners'. A software house for instance may sell standard software applications, for which it has dedicated product development lines. At the same time, it can provide custom-made software applications, for which project managers are responsible. De Boer (1998) uses the term 'semi-project-driven' to describe such organisations. Although this is certainly a pertinent remark, we do not specifically distinguish between project-driven and semi-project-driven organisations in this text. The techniques we study are applicable to the project-based part of organisations, whether this constitutes all or only part of those organisations.

This paper is organised as follows. First, we survey the existing approaches to practical multi-project planning (Section 2). In Section 3 we discuss hierarchical

planning and control frameworks that can be found in the literature, including the framework that we use in this paper. Sections 4 and 5 treat the tactical and operational aspects of planning in further detail. We mainly focus on methods for the *tactical* Rough Cut Capacity Planning (RCCP) problem and the *operational* Resource-Constrained Project Scheduling problem (RCPSP). In Section 6, we set out a number of requirements such that these two levels can be integrated, and we discuss in which situations each of the hierarchical levels deserves the most attention. In Section 7 we discuss two practical examples of multi-project organisations, for which the hierarchical approach combined with the appropriate planning methods would be beneficial or have been successfully implemented. We end this article with some conclusions (Section 8).

2 Multi-project management

This section is devoted to multi-project *management*, the broader management discipline that encompasses the *planning* function that is the main target of this paper – we may use the two terms 'multi-project management' and 'multi-project planning' interchangeably in the remainder of this text. The focus of Section 2.1 is on the planning aspect of multi-project management. In Section 2.2 we discuss organisational aspects of multi-project management. We present a positioning framework for multi-project management in Section 2.3.

2.1 *Multi-project management*

Adler et al. (1995, 1996) suggest adopting a process viewpoint to multi-project management. They remark that most managers think of multi-project management simply as the management of a list of individual projects, rather than as a complex operation with a given capacity and workload. Their suggestion is compatible with

the introduction of a 'Management by Projects' (MBP) orientation at enterprise level, which takes the benefits of project management with its focus on specific project goals and deliverables as a starting point, but builds it into the needs of the overall organisation. As such, MBP is the integration, prioritisation and continuous control of multiple projects and operational schedules in an enterprise-wide operating environment (Boznak, 1996; Advanced Management Solutions, 2003). Various approaches for "multi-project management and planning" have been proposed in the literature. *Real* multi-project approaches that are compatible with an MBP focus, however, are scarce.

Pennypacker and Dye (2002b) point out that there still exists a difference between multi-project management (with the same content as what we defined as 'MBP') and *project portfolio management*. The former is geared towards operational and tactical decisions on capacity allocation and scheduling, and is the job of project or resource managers; the latter is concerned with project selection and prioritisation by executive and senior management, with a focus on strategic medium- and long-term decisions. Finally, multi-project management should also not be confused with *program management*, which is a separate concept altogether: program management is a special case of multi-project management that has a single goal or purpose (for instance putting a man on the moon), whereas multi-project management generally treats the case of multiple independent goals (Wysocki et al., 2002). A *program* can be seen as a family of related projects.

In the project-based part of the organisations, projects compete for the same scarce resources. Unfortunately, many multi-project approaches do not recognise this and treat the multi-project planning problem as a set of independent single-project planning problems. In this way, the typical 'resource conflict' that emerges when managing multiple concurrent projects is overlooked. Moreover, many so-

called advanced planning systems lack a multi-project planning function at the aggregate capacity level. Often this lack is filled with an 'aggregate scheduling' module, which is not capable of utilizing the capacity flexibility at the tactical level.

Nevertheless, an aggregate, combined project plan is a good help for management to ensure that the organisation does not take on more projects than it can complete (Wheelright and Clark, 1992); it also facilitates cross-project analysis and reporting (Kerzner, 1998). Maintaining integrated plans is difficult, however, because of the uncertainty inherent to each individual project, the size of the projects, the dynamic nature of the project portfolio, and the fact that different projects usually have different project managers with differing or even conflicting objectives. Reiss (2002) also discerns a number of problems that can arise with the (IT-aspects of) consolidation of individual project plans.

In order to adequately perform multi-project planning, projects must be considered simultaneously at all planning levels, while taking into account that those different levels have different objectives, constraints and degrees of aggregation. These objectives are, for instance, the optimal timing of operations for the operational level, optimal resource management for the tactical level, and the robustness or stability of plans for all levels. Multi-project management approaches must deal with these objectives hierarchically. The techniques we study are applicable to the project-based part of organisations and can handle the varying objectives of complex multi-project organisations.

2.2 *Organisational aspects of multi-project management*

From Meredith and Mantel (2003), it can be remarked that, any time a project is initiated, whether the organisation is only conducting a few occasional projects or is rather fully project-oriented and carrying on scores of projects, it must be decided

how to tie the project to the parent firm, especially to its resources. Meredith and Mantel distinguish three major organisational forms commonly used to house projects within an enterprise. We briefly discuss these three methods.

A first alternative for situating the project within the parent organisation is to make it entirely *part of one of the functional divisions* of the firm. It is clear that this option is only possible when the activities particular to the project are all strongly tied to the function performed by the functional division it is embraced by.

At the other end of the organisational spectrum, we find a *pure project organisation*. The project is separated from the rest of the parent system and becomes a self-contained unit with its own dedicated staff and other resources. Single-project management techniques at the operational level normally suffice for these cases. This structure has the obvious disadvantage of duplication of effort in multiple functional areas and may induce sub-optimisation of project goals rather than overall organisation objectives. On the other hand, the project can function autonomously with clear focus, and need not worry about conflicts with other projects or with functional departments.

The *matrix structure* is an intermediate solution between the two extreme organisational models discussed above, attempting to combine the advantages of both and to avoid some of the disadvantages of each form. Resources are associated to functional departments but are assigned to different ongoing projects throughout time. The strength of the link of resources between their functional department and their current project(s) allows a wide range of different organisational choices. Assuming a 'balanced' matrix structure (not yielding towards any of the extremes), the multi-project organisation can be modelled from a process viewpoint as a job shop or assembly shop: work is done by functional departments that operate as workstations and projects are jobs that flow between the workstations.

2.3 *A positioning framework for multi-project organisations*

To distinguish between various multi-project organisations we propose a positioning framework that will allow us to categorise the various forms of multi-project environments based on their characteristics. Earlier in this paper we cited *variability* and *complexity* as two key concepts that are often used in literature about hierarchical project management. Shenhar (2001) for instance argues that not all projects have the same characteristics with respect to *technological uncertainty* and *system complexity*, and uses these two concepts to define a framework in which he positions several practical projects. His framework is the starting point for a discussion of managerial styles that are best suited for particular project environments. Shenhar (2001) does not consider environments in which multiple projects are executed simultaneously. Unfortunately, *variability*[4] and *complexity* are not mutually exclusive: complexity being a far broader concept, it entails variability.

Leus (2003) and Herroelen and Leus (2003) describe a methodological framework to position project planning methods, in which they distinguish two key determinants: the degree of general *variability* in the work environment and the degree of *dependency* of the project. The 'variability' is an aggregated measure for the uncertainty because of, on the one hand, the lack of information in the tactical stage and/or, on the other hand, operational uncertainties on the shop floor. The 'dependency' measures to what extent a particular project is dependent on influences

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[4] Decision theory distinguishes between risk and uncertainty. In a *risk* situation, the distribution of the outcomes is known with certainty for each management option, while the link between decisions and outcomes is not known under *uncertainty*. The term *variability* seems to apply especially to a risk situation. Nevertheless, we will use the terms 'variability' and 'uncertainty' more or less interchangeably throughout this paper.

external to the individual project. These influences can be actors from outside the company (e.g. subcontractors or material coordination), but also dependencies from inside, for instance shared resources with other projects. Dependency forms part of the complexity of the planning of a project-based organisation (as referred to in Section 1), and is the key complexity component we distinguish. It will strongly determine the organisational structure (see Section 2.2), although this choice is not always exclusively based on the characteristics of the company. Other factors may also play a role, such as unwillingness to change: choices that have been determined historically are sometimes hard to undo, even though better alternatives might be available under new circumstances.

The resulting framework is depicted in Table 1. We consider the scale of the dimensions to be continuous. For simplicity we discuss the four extreme cases of Low and High variability and Low and High dependency. Nevertheless, all possible intermediate positions in between the four extreme cases are conceivable. We provide the table with a case-by-case comment.

Table 1. A positioning framework for multi-project organisations.

Dependency Variability	LOW ⟶ HIGH	
LOW ↓ HIGH	LL	LH
	HL	HH

LL: Low variability and a low dependency can typically be found in a dedicated single-project organisation. In such organisations, resources are completely dedicated to one particular project and activities have a low degree of uncertainty. An example is an on-site maintenance project, which is performed on a

preventive basis. Activities of these projects are often specified in advance and executed routinely. Therefore the degree of uncertainty is relatively low. Moreover, such maintenance projects often have little interaction with other projects, so the degree of dependency is also low.

LH: In this project environment many project activities are dependent on external actors. One can think for instance of a small furniture manufacturer that produces wooden furniture on a make-to-order (MTO) basis (e.g. chairs, beds, etc). Most operations in such a company will be executed on universal woodworking machines like drills, saws and lathes. Hence, the manufacturing process will be relatively basic, which will result in a low degree of operational variability. Moreover, *variability* resulting from uncertainties in the process planning stage is relatively low because of the low degree of complexity of the products and the production processes. In contrast to the low variability in this setting, dependency of projects in this environment can be high because of many projects that may claim the same woodworking machines at the same time. This *LH*-setting is most related to the classical job shop.

HL: An environment with high variability combined with a low degree of dependency can be found, in for instance, large construction projects. These construction projects are typically subject to large environmental uncertainties such as bad weather conditions, uncertain or changing project specifications. The degree of dependency on other projects is typically low because, in view of the size of general construction projects, the deployed resources are often dedicated.

HH: A high degree of uncertainty in combination with highly dependent projects can typically be found in engineer-to-order (ETO) environments with several complex projects in parallel. These projects are typically completely new to the company, which results in a long engineering trajectory and many disruptions and

adaptations because of changes imposed by for instance the customer. As an example, we can mention a company that manufactures welding equipment for the automotive industry. Every product is designed for a specific (new) car. Therefore, every new product requires a long and intensive engineering process. Moreover, the customer may frequently require modifications of the design. Combining this with the complexity of the product results in a project environment that has an extremely high degree of variability. Furthermore, such manufacturers often produce multiple products simultaneously, which also results in a high degree of dependency between the projects.

A project that is situated in the *HH*-category requires planning and control approaches that can deal with both the organisational complexity and the variability as well as with the complexity of the planning problem. Clearly, the lower right quadrant of the positioning framework is most difficult to manage. This paper provides a planning and control framework and discusses several planning techniques that can deal with high variability and a high degree of dependency at the same time. Moreover, we discuss the interaction between the proposed planning techniques on the different hierarchical levels.

3 Hierarchical frameworks for planning and control

Various hierarchical planning and control frameworks for manufacturing and project environments have been proposed. In Section 3.1 we survey the existing literature on hierarchical planning and control frameworks for *multi-project planning*. Section 3.2 investigates the related subject of hierarchical planning and control for *manufacturing environments*. Finally, in Section 3.3, we present the hierarchical planning and control framework that is used in the remainder of this paper.

3.1 *Hierarchical planning and control for project organisations*

Fendley (1968) is an early reference; he discusses the development of procedures for the formulation of a complete multi-project scheduling system that uses: (1) a method for assigning due dates to incoming projects, and (2) a priority rule for sequencing individual jobs such that total costs are minimised (heuristically). Fendley points out that, because of the uncertainty of performance times, it is almost impossible to maintain an advance schedule in a multi-project organisation. What can and should be determined in advance, the author says, is a delivery date or due date for each project by which the organisation desires to have completed the project. He remarks that since the performance times of the activities are uncertain, the sequencing of the individual activities must be handled on a dynamic basis.

Leachman and Boysen (1985) and Hackman and Leachman (1989) describe a two-phase hierarchical approach. In the first phase, due dates are selected for new projects and resources are allocated among projects based on an aggregate analysis. An aggregate model of each project is developed by aggregating detailed activities with similar mixes of resource requirements into aggregate activities. Given actual due dates for committed projects and trial due dates for proposed projects, the aggregate project models are then combined in a multi-project resource allocation model that is formulated as a linear program. The linear program minimizes the discounted cost of unused resources, i.e. the present value of cost overruns associated with charging ongoing projects for unutilized resources. The authors suggest to iteratively solve linear programs and revise trial due dates until a desirable resource loading plan has been developed. Both the selected due dates and the computed resource allocations define the single-project scheduling problems to be addressed in the second phase.

Kim and Leachman (1993) describe another hierarchical methodology to schedule multi-project environments under the objective of minimising total project lateness costs. In the first stage, target resource profiles are computed for each project as convex combinations of the early and late cumulative resource curves associated with the earliest- and latest-start CPM schedules. These target resource levels then serve as decision aids for regulating the progress speeds of the projects during detailed activity scheduling using a heuristic procedure based on the variable-intensity model proposed by Leachman et al. (1990).

Speranza and Vercellis (1993) remark that little effort has been devoted to a structured quantitative approach that addresses the issue of integration between the tactical and the operational stages of the project planning process. They propose to distinguish between a tactical and an operational level with different planning objectives at each level. On the tactical level due dates are set and resources are allocated. On the operational (service) level the activity modes are set and the timing of the activities is determined. Their approach is based on the assumption that a set of aggregated activities forms a macro-activity on the tactical level. If these macro-activities are interrelated by means of precedence relations, they form a program. It should be mentioned that Hartmann and Sprecher (1996) have provided counterexamples to show that the algorithm may fail to determine the optimum.

Yang and Sum (1993, 1997) propose to use a dual-level structure for managing the use of resources in a multi-project environment. A central authority (resource pool manager or director of projects (Payne, 1995)) negotiates the project due dates with the customer, determines the allocation of resources among projects such that resources are allocated to the critical projects, and decides on the project release dates. The lower-level decisions of scheduling the activities within each project are managed by an independent project manager who schedules the activities

of his project using only the resources assigned to him. Yang and Sum (1993) examine the performance of heuristic resource allocation and activity scheduling rules. Yang and Sum (1997) investigate the performance of rules for due date setting, resource allocation, project release, and activity scheduling in a multi-project environment, where significant resource transfer times are incurred for moving resources from one project to another.

Franck et al. (1996) propose a capacity-oriented hierarchical approach for hierarchical project planning with project scheduling methods. They distinguish several planning problems as for instance lot sizing, capacity planning, and shop floor scheduling. They formulate optimisation models that resemble the deterministic resource-constrained project scheduling problem. They do not distinguish between the different planning objectives of the various planning levels.

Dey and Tabucanon (1996) propose a hierarchical integrated approach for project planning. They discuss different planning objectives at different planning levels and they use goal programming techniques to solve the corresponding planning problems. Nevertheless, they do not use a multi-project approach.

De Boer (1998) proposes a hierarchical planning framework for project-driven organisations. He argues that a hierarchical decomposition is needed to come to a more manageable planning process. He also mentions that, especially in project environments, uncertainties play an important role. De Boer argues that if uncertainties are too large, channels in hierarchical structures become overloaded with information. He propose four strategies to prevent this: (a) the creation of slack by lowering output targets; (b) the creation of self-contained activities, i.e. large tasks that can be executed by multi-disciplinary teams; (c) the creation of lateral linkages using e.g. a matrix organisation or special teams; and (d) investment in vertical information systems. He argues that these strategies are an effective way to deal with

uncertainty in project driven organisations, however, like many other authors, he does propose *deterministic* planning techniques at the separate planning levels, which do not explicitly account for uncertainties.

Neumann et al. (2003) (see also Neumann and Schwindt, 1998) present and illustrate a three-level hierarchical multi-project planning process under the assumption that a portfolio of long-term projects is to be performed within a planning horizon of two to four years. Each project has a given release date, deadline and work breakdown structure, i.e. it consists of subprojects, which include different work packages, each of which can be decomposed into individual activities. At the first level (long-term) all the projects are grouped into a single multi-project network that contains all the subprojects as aggregate activities. The release date and deadlines are modelled using generalised precedence relations. The aggregate activities are to be scheduled subject to scarce key resources (e.g. experts, research equipment, special-purpose facilities). The estimated duration of an aggregate activity equals the critical path length of the corresponding subproject plus a time buffer that anticipates the time extension of the aggregate activity that will occur due to the scheduling of the disaggregated projects at the third planning level. Neumann et al. suggest to estimate the size of the time buffers using queuing theory. The key resource requirement of an aggregate activity is computed as the ratio of the total workload of the corresponding subproject and its pre-estimated duration. The capacity of the key resources is fixed by the general business strategy. The financial objective function is the maximisation of the net present value of the project portfolio. The resulting schedule provides a maximum duration for every project and the resulting resource profiles provide the time-dependent resource capacities for the key resources at the second planning level. At the second level (medium-term) each project is condensed by choosing the aggregate activities to be the work packages.

The durations, time lags and resource requirements are determined analogously to what happened at the first level. At the second level Neumann et al. also consider primary resources (technical and administrative staff or machinery) with unlimited availability. The objective is to level the use of these resources over the project duration. At the third planning level (short-term) the condensed projects are disaggregated into detailed projects with individual activities. Resource constraints are given for the key and primary resources as well as for low-cost secondary resources (tools, auxiliary resources). The objective is to minimize the project duration.

3.2 *Hierarchical planning and control for manufacturing organisations*

The majority of the work on *hierarchical production planning* (HPP) focuses on manufacturing environments rather than project environments. Some authors argue that shop floor planning is a specialization of multi-project planning. We adhere to this point of view for the discussion of hierarchical planning and control frameworks. Therefore, we also discuss work on hierarchical planning and control frameworks for shop floor manufacturing environments. A fundamental study on hierarchical production planning is that of Hax and Meal (1975). After this, several articles on hierarchical integration of different planning functions followed, for instance, Bitran et al. (1982), Bitran and Tirupati (1993), Bertrand et al. (1990), Hax and Caneda (1984) and Vollmann et al. (1997).

In a review article about intelligent manufacturing and control systems, Zijm (2000) remarks that in practice the existing hierarchical planning approaches have proven to be inadequate for several reasons. The main reason is that the existing planning frameworks are either material-oriented (e.g. MRP / MRP II systems) or capacity-oriented (HPP systems). Zijm proposes a hierarchical framework that

focuses on the integration of technological and logistics/capacity planning, and the integration of capacity planning and material coordination. Zijm also mentions that there is a lack of appropriate aggregate capacity planning methods at the order acceptance level. In order to fill this gap, Hans (2001) proposed several deterministic models and techniques to solve the aggregate (tactical) capacity planning problem, which he refers to as the resource loading problem. With these deterministic techniques a planner can quote reliable due dates and estimate the capacity requirements over a time horizon of several weeks to several months. Hans claims that these methods can also be used for multi-project capacity planning in project environments. Kolisch (2001) proposes a hierarchical framework to distinguish between the managerial processes in make-to-order manufacturing. He distinguishes three processes/levels, namely, the order selection level, the manufacturing planning level, and operations scheduling level. He also proposes deterministic models for the various levels.

From this short review of hierarchical production planning and control frameworks we can conclude that several frameworks have been proposed for shop floor oriented manufacturing environments and for project-driven organisations. Only few, however, actually deal with different objectives of the planning problems at different levels. Moreover, little effort has been devoted to the aspect of uncertainty in the hierarchical multi-project planning approach, the integration of technological planning and logistics planning, and the integration of material coordination and capacity planning.

3.3 *Hierarchical planning and control for multi-project organisations*

We propose a hierarchical project planning and control framework that is partly based on the framework that was proposed by De Boer (1998). We have adapted the

framework to be able to discern the various planning functions with respect to material coordination and technological planning. As shown in Figure 1, we distinguish three hierarchical levels: (a) the strategic level, (b) the tactical level, and (c) the operational level. We distinguish three functional planning areas: (a) technological planning (b) capacity planning, and (c) material coordination.
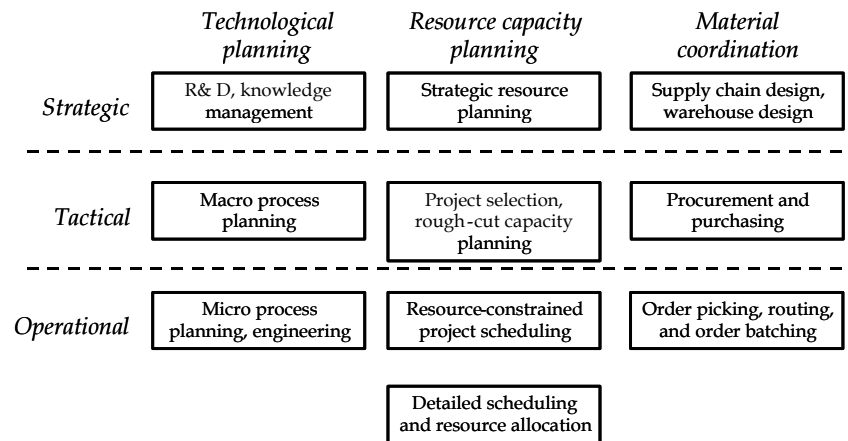
	Technological planning	*Resource capacity planning*	*Material coordination*
Strategic	R& D, knowledge management	Strategic resource planning	Supply chain design, warehouse design
Tactical	Macro process planning	Project selection, rough-cut capacity planning	Procurement and purchasing
Operational	Micro process planning, engineering	Resource-constrained project scheduling	Order picking, routing, and order batching
		Detailed scheduling and resource allocation	

Figure 1. Hierarchical framework.

In this hierarchy we define four capacity planning functions: (a) strategic resource planning; (b) rough-cut capacity planning (RCCP); (c) the resource-constrained project scheduling problem (RCPSP), and (d) detailed scheduling. Contrary to De Boer, we position both the RCPSP and the detailed scheduling and resource allocation problem at the operational level. Since RCPSP and resource allocation are two different problems (Leus, 2003) we treat them separately. In Sections 4 and 5 we elaborate on the tactical (RCCP) and operational (RCPSP) planning level.

Note that at each level of the hierarchy, the positioning framework of Table 1 can be applied. Some organisations are characterised by a high degree of uncertainty on the operational level whilst on the tactical level the uncertainties are much more controllable. On the other hand the dependency of projects in some companies may

be considerable on the tactical level while projects are completely independent on the operational level. These differences play an important role in modelling the interactions between the hierarchical planning levels; we will we elaborate on this issue of interaction between the levels in Section 6.

4 Rough-Cut Capacity Planning

In the early project stages, projects may vary significantly with respect to routings, material, tool requirements, or the work content of activities. In spite of the uncertain project characteristics, project accept/reject decisions must be made, and important milestones (such as the due date) must be set. It is common practice that companies accept as many projects as they can possibly acquire, although the impact of a decision on the operational performance of the production system is extremely hard to estimate. Moreover, to acquire projects, companies tend to promise a delivery date that is as early as possible. This is generally done without sufficiently assessing the impact of these projects on the resource capacity. This may lead to a serious overload of resources, which has a devastating effect on the delivery performance and the profitability of the production system as a whole.

Customers require reliable project due dates as part of the service mix offered by the company during order negotiation. Being able to quote tight and reliable due dates is a major competitive advantage. Therefore, at the negotiation and acceptance stage, adequate Rough-Cut Capacity Planning (RCCP) methods that assess the consequences of decisions for the production system are essential. Contrary to the operational planning level, the tactical planning stage is characterised by a high degree of capacity *flexibility* (e.g. by working in non-regular time or by subcontracting). Tactical planning therefore requires methods that use more aggregate data, and that can exploit this capacity flexibility. Ideally, RCCP-methods

should use this flexibility to support a planner in making a trade-off between the expected delivery performance and the expected costs of exploiting flexibility by using non-regular capacity.

Adequate deterministic planning approaches for the RCCP-problem were proposed by De Boer (1994), Hans (2001) and Gademann and Schutten (2001). These tactical planning approaches all use an objective function that minimises the cost of using non-regular capacity in period t (i.e. overtime (O_t), hiring additional staff (H_t) and subcontracting (S_t)), which results in the objective $min(s*S_t +h*H_t +o*O_t)$, in which s, h, and o represent the cost parameters associated with the decision variables S_t, O_t, and H_t. In the remainder of this paper we use the symbol S_t for the decision variable that indicates the use of nonregular capacity in period t. De Boer (1994), Hans (2001) and Gademann and Schutten (2001) implicitly claim that for project environments that are in the LL- and LH-categories it suffices to choose a proper data-aggregation level to cope with the disturbances that might occur. Although this assumption may be justified for environments that are in the area of LL and LH, it is to be noted that for project environments in the HL and HH area of our positioning framework, restriction of attention to the choice of a proper data-aggregation level and deterministic planning approaches is not sufficient.

We believe that all planning methods should be able to deal with the uncertainties that are typical for the particular planning level they work on. These uncertainties may range from unexpected operational events (e.g. machine breakdowns or operator unavailability) to uncertainties that typically result from the lack of information at the concerned project stage. The former category of uncertainties is typically dealt with at the operational planning level. The latter category typically arises in the earlier project stages, and is handled at the tactical (RCCP) level. Elmaghraby (2002) affirms that the work content of an activity is one of

the most important sources of uncertainty. He claims that resource capacity management methods that can deal with these uncertainties have a decisive impact on the overall performance of a project-driven organisation. Uncertainties that can be considered in RCCP-models are for instance the work content of an activity, activity occurrence, resource availability or, release and due dates. In general, the deterministic models for RCCP have been developed under the assumption that the aforementioned uncertainties are dealt with by using a proper level of aggregation and by reserving additional resource capacity. Few planning approaches explicitly take into account uncertainty at the RCCP-stage.

Wullink et al. (2003) propose a proactive approach to deal with the RCCP-problem under uncertainty. They use a scenario approach to model uncertain work content of activities. With a scenario-based MILP-model they minimise the expected costs of using non-regular capacity. This results in the objective $min(E[s*S_t])$, in which s is a cost parameter with the decision variable S_t. The scenario-based approach results in considerable improvements with respect to the expected costs over all scenarios of a plan compared to the previously proposed deterministic approaches.

Deterministic approaches for RCCP as proposed by De Boer (1994), Hans (2001) and Gademann and Schutten (2001) optimise a single-cost objective. From a purely mathematical point of view this suffices to solve the deterministic problem. Nevertheless, taking into account uncertainties may require other objectives. For instance, the robustness of a plan may be incorporated in the objective. An example of such a robustness criterion (R_t) estimates the ability of a plan to absorb disturbances. Using this robustness indicator results in a second approach for RCCP under uncertainty, which minimises the weighed sum of the costs of using nonregular capacity and a robustness criterion (i.e. $min(s*S_t + r*R_t)$), in which s and r represent the weighing coefficients for the nonregular capacity and the robustness.

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This approach allows a trade-off between the robustness and the use of nonregular capacity.

In general, mathematical optimisation techniques focus on *optimality* of a solution. If an optimum is reached the problem is generally considered as solved satisfactorily. Usually, alternative solutions with equivalent or almost equivalent values for the objective functions are discarded. Nevertheless, these solutions might provide an improvement with respect to other criteria than the initial objective, such as for instance robustness. One can think of generating a set of solutions that contains Pareto-optimal solutions on two or more criteria. With these Pareto optimal solutions a planner can make a trade-off between costs and robustness. Moreover, such an approach allows a planner to assess several plans on more practical characteristics that are difficult to quantify, but that are generally implicitly taken into consideration during the planning process (e.g. whether a plan is workable in practice, or the degree in which an activity is spread over the periods).

The approaches to deal with uncertainty on the tactical level we have discussed so far are all *proactive* approaches. These approaches aim at anticipating uncertain events. *Reactive* methods for tactical planning are also possible, which normally use one or more replanning rules that are applied when a disturbance occurs, in order to generate a new plan. Most companies already apply reactive planning by updating their plans with a certain frequency or when existing plans have become infeasible.

5 Resource-Constrained Project Scheduling

Our focus in this section is on the simultaneous scheduling of multiple projects. Apart from the hierarchical multi-project planning schemes discussed in Section 3.1, existing research efforts in multi-project scheduling have mainly assumed a single-

level structure where a single manager oversees all projects and where the resource transfer times for moving resources from one project to another are negligible. In a first approach, projects are artificially bound together into a single project by the addition of two dummy activities representing the start and end of the single 'aggregate' project, possibly with different ready (arrival) times and individual due dates. In such a case, existing exact and suboptimal procedures for single-project scheduling may be used for planning the aggregate project.

In a second approach, the projects are considered to be independent and specific multi-project scheduling techniques – mostly heuristic in nature – are used. Kurtulus and Davis (1982) report on computational experience obtained with six priority rules under the objective of minimizing total project delay. Kurtulus (1985) and Kurtulus and Narula (1985) analyse the performance of several priority rules for resource-constrained multi-project scheduling under equal and unequal project delay penalties. Lova et al. (2000) have developed a multi-criteria heuristic for multi-project scheduling for both time-related and time-unrelated criteria. Lova and Tormos (2002) have developed combined random sampling and backward-forward heuristics for the objectives of mean project delay and multi-project duration increase.

Several authors have studied the problem of assigning due dates to the projects in a multi-project environment. Dumond and Mabert (1988) evaluated the relative performance of four project due date heuristics and seven resource allocation heuristics; related research can be found in Dumond (1992). Bock and Patterson (1990) investigate several of the resource assignment and due date setting rules of Dumond and Mabert (1988) to determine the extent to which their results are generalisable to different project data sets under conditions of activity pre-emption. Lawrence and Morton (1993) study the due date setting problem and performed large-scale testing of various heuristic procedures for scheduling multiple projects

with weighted tardiness objective. Several model extensions are discussed in Morton and Pentico (1993).

As we mentioned earlier in Section 3.1, in a hierarchical project management system, due dates are usually set on the tactical level. Yang and Sum (1997) determine due dates on the first level of their suggested dual level structure. They reach conclusions that are consistent with the ones reported in the references listed in this section. The use of information that goes beyond critical path length and number of activities and takes into account the work content of the projects provides better due dates. They also conclude that the relative performance ranking of the due date rules is unaffected by the presence of customers' control over the due dates nor by the choice of the other decision rules for resource allocation, project release and activity scheduling. In our hierarchical framework shown in Figure 1, we assume that due dates are set on the rough-cut capacity planning level.

All the methods described so far in this section schedule the project activities for efficiency in a deterministic environment and under the assumption of complete information. During execution, however, the project is subject to considerable uncertainty, which may lead to numerous schedule disruptions – we refer the reader to the *variability*-dimension of Table 1. This variability factor in the framework involves a joint impression of the uncertainty and variability associated with the size of the various project parameters (time, cost, quality), uncertainty about the basis of the estimates (activity durations, work content), uncertainty about the objectives, priorities and available trade-offs, and uncertainty about fundamental relationships between the various project parties involved. It should be clear that reliable and effective rough-cut capacity planning will also have a strong beneficial impact on variability at the operational level.

When dependency and variability are both low (case *LL*), deterministic

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single-project scheduling methods can be used to schedule each individual project in a multi-project environment: the project can be planned and executed with dedicated resources and without outside restrictions. For case *HL*, with high variability and low dependency, a detailed deterministic schedule covering the entire project will be subject to a high degree of uncertainty. Dispatching of individual activities according to some decision rule (without prior overall schedule) is possible, since the resources are available almost 100% to the project. Alternatively, a reactive approach can be followed: *reactive scheduling* revises or re-optimises the baseline schedule when unexpected events occur. *Proactive schedules* are schedules that are as well as possible protected against anticipated schedule disruptions that may occur during project execution. Proactive scheduling techniques can be applied to enhance the quality of objective function projections in reactive scheduling.

In the high-dependency case (the right column of Table 1), a large number of resources are shared and/or a large number of activities have constrained time windows. A *stable* plan should be set up for these activities, such that small disruptions do not propagate throughout the overall plan. Stability is a particular kind of robustness that attempts to guarantee an acceptable degree of insensitivity of the activity starting times of the bulk of the project to local disruptions; for more details on stability in scheduling we refer to Leus (2003). *Satisficing* may be required to obtain a feasible plan with a minimal number of (for instance resource) conflicts. Case *HH* is best seen from a process management viewpoint: the resources are workstations that are visited by (or visit) work packages and pass these on to the appropriate successor resources after completion. A rough ballpark plan can be constructed to come up with intermediate milestones, which can be used for setting priorities for the resources in choosing the next work package to consider.

Intermediate cases with moderate dependency may benefit from an

identification of what we refer to as the *drum* activities: these are the activities that induce the dependency. Either they are performed by shared internal or external resources, or their start or completion time is constrained. It may make sense to adopt a two-level scheduling pass, planning the drum activities first and the remaining activities afterwards. The drum can be scheduled either efficiently or in a stable manner; the remainder activities can either be scheduled from the start or rather dispatched in function of the progress on the drum.

6 Interaction of the hierarchical levels

Planning approaches on the various hierarchical levels cannot operate independently from each other. Information that is generated by other (planning) functions in the framework should be exploited to the best possible extent. More specifically, it should be clear which information is passed down form high to low levels and vice versa. Several authors have discussed the interaction between the various hierarchical planning levels with a focus on manufacturing organisations. Krajewski and Ritzman (1977) give a survey of a disaggregation approach in manufacturing and service organisations. For a multi-stage system with multiple products and nonlinear assembly trees they state that this problem is hard to solve because of its computational complexity. Therefore, they propose to use MRP for this problem. It should be noted, though, that it in generally MRP is not suitable for MTO and ETO environments.

Kolisch (2001) remarks that assemblies and subassemblies should be exploded into individual operations with detailed resource requirements, and that resources be differentiated with respect to their specific qualifications. Most authors, however, do not describe the actual interaction and the information that is exchanged between the planning levels. We will discuss this interaction between the

various hierarchical levels according to the positioning framework proposed in Section 2.3. For our analysis, we distinguish between project-driven organisations with low and high dependency.

Project organisations with high dependency (*LH* and *HH*) generally adopt a matrix-organisational structure. For this type of multi-project organisations, we propose to exchange information between the tactical and operational planning levels in the following way. In the early stages of the project when only rough information about the project content is available, the most important output of RCCP-methods are internal and external due dates, milestones and required capacity levels. This information will serve as the basis for acquiring additional resources if necessary, ordering raw materials and final fixing of due dates. In a later stadium, more information becomes available gradually as more preparatory work is performed. These data are combined with information generated by process planning and design and passed on as input for the operational planning phase. Operational planning itself consists of a multi-project RCPSP, as discussed in Section 5.

The other two cases in our framework (*LL* and *LH*) correspond to the other end of the organisational spectrum, i.e. the dedicated or pure project organisation. For this kind of organisations we propose a different way of interaction. Here, resources are dedicated to a specific project, and so the assignment of resources to projects can already be done in the tactical stage. Therefore, besides the information that was exchanged between the hierarchical levels in the *HH* and *HL* cases (i.e. due date, milestones and capacity levels), resource allocation decisions are also passed down to the operational level in cases *LH* and *LL*. Consequently and as already pointed out in Section 5, the subsequent operational planning problem is single-project oriented: multiple separate single-project plans are developed at the

operational level.

For clarity of exposition, the foregoing paragraphs have described two extreme forms of interaction, but in practice, intermediate solutions may of course be required. We have also focused solely on the capacity planning aspects of the interaction. Obviously, there is an exchange of a lot of additional information between the hierarchical levels that we have left unmentioned, for instance in the domain of technological planning and material coordination.

7 Practice

In this section we discuss two research projects that took place at Dutch companies. One case concerns the implementation of a hierarchical multi-project planning approach in the ship repair industry. The second case is a typical example of a project-driven environment that can be characterised as a *HH* environment.

7.1 *Royal Netherlands Navy Dockyards*

This short case is an example of a successful implementation of a hierarchical decision support system at a large project-driven organisation, a typical example of a multi-project environment with a high degree of dependency. Variability is mostly limited and is therefore not explicitly dealt with by advanced quantitative techniques. The Royal Netherlands Navy Dockyard is a public company that is responsible for the maintenance, repair and modification of national defence marine equipment. Three sorts of maintenance can generally be distinguished, namely appointed incidental maintenance, incidental maintenance, and intermediate maintenance. Maintenance of the last category is planned on a long-term basis. The organisational structure is purely functional: resources are associated with a functional department.

Before implementing a hierarchical Decision Support System (DSS) system the situation was as follows. Before the start of the project, the dockyard made all tactical planning decisions like determining due dates, or hiring additional personnel. To support these decisions, the process planning function had to come up with a lot of estimations about e.g. the duration of detailed operations. In this way, too many data were needed in early stages of the projects to support order acceptance, capacity requirements estimations, and the determination of important milestones for the project. In other words, the tactical decisions were made based on numerous and often imprecise estimations, which resulted in countless adjustments of the detailed plan when new information became available at later stages of the project. If we use our positioning framework proposed in Section 2.2 we can see that for the tactical level this environment can be typified as a *HL* environment. The degree of uncertainty varies over the projects depending on the project type, but is mainly of an operational nature. Incidental projects could be much more uncertain then intermediate projects, however, there is always a large degree of dependency between projects.

In his PhD-thesis, De Boer (1998) describes the implementation of a hierarchical DSS for multi project planning at the Royal Netherlands Navy Dockyard. He argues that if organisations are too large for coordination by simple adjustment of data, a hierarchy is needed to deal with the uncertainty. In other words, when necessary because of a large number of disruptions and exceptions, a hierarchical structure facilitates the downward delegation of responsibilities. The DSS that De Boer proposes contains two hierarchical levels: a tactical RCCP-level and an operational RCPSP-level. Applying a hierarchical DSS with at each level the appropriate quantitative planning approach has turned out to be successful. Deterministic planning approaches are used to solve the RCCP and RCPSP problems.

The main motivation for this choice is the lack of adequate planning approaches that account for uncertainties. The last few years, however, planning techniques that account for uncertainty have been emerging and may be embedded in the DSS. This would allow generating robust and stable plans for this complex multi-project planning environment.

7.2 *REPRO*

This case is an example of a multi-project environment with a high degree of dependency and a high degree of variability (*HH*). We discuss this case to illustrate the need for multi-project planning approaches that can deal with the organisational complexity and the uncertainty that characterises the environment as well as with the complexity in the planning process.

The REPRO project aimed at improving the productivity of several large Dutch ship repair yards in Rotterdam and Amsterdam. One of the most important characteristics of the ship repair industry is the uncertainty of activities in repair projects. Consider for instance a ship that has had a collision at sea. Suppose the damage of the ship is (mainly) under the water level, so an inspection to establish the extent of the damage is impossible without dry-docking the ship. It is therefore hard to estimate the duration of the repair project. Nevertheless, in the negotiation process with a ship repair yard, a due date has to be established. The competition in the repair industry is fierce so the shipyard wants to quote a competitive due date. Nevertheless, if the quoted due date is not met, high delivery penalties may be charged.

Once a ship is at the yard for repair, a project leader is assigned to the ship, and repair starts immediately. At the time of investigation, the organisational structure resembled a matrix structure, but there was no overall planning mechanism

for assigning resources to projects. Planning of projects was limited to CPM-computations and capacity constraints were completely ignored. This resulted in each project leader claiming as much workforce as he could possibly obtain, in order to make sure that he could achieve his goal, which is completing his ship in time. At the same time, other project leaders competed for the same resource capacity. This single-project approach resulted in an unbalanced and inefficient use of resource capacity. One week the yard needed a huge amount of external workforce to complete a project in time, the other week a large part of the workforce was sent home because of a lack of work.

At the ship repair yards considered in this project the operational planning was considered to be too uncertain to be performed in advance. Rough tactical planning (CPM-based) was used to manage the operations on the shop floor. It was claimed that the projects were too uncertain to be planned at all, so only rough estimates of the lead-time were made. The sequence of operations is generated on the shop floor using straightforward dispatching rules based on common sense of foremen.

This is a typical example of a *HH* project organisation. Uncertainties are high and projects are dependent. In our opinion, robust multi-project planning methods for the tactical level could yield better-balanced resource utilization and more reliable due dates. For the operational planning, if uncertainty is too high, dispatching is indeed in order, but simple deterministic scheduling approaches combined with replanning rules are preferable for moderate uncertainty. If projects get larger and better documented, more advanced robust scheduling approaches might be useful: a stable initial plan (not overly detailed) can determine the pace of the project. This is an example that illustrates that not every environment is suitable for the most advanced planning techniques, at least not from the start. If possible, variability

reduction techniques should be applied, and the operational scheduling level need not receive too much attention before the broader tactical decision-making process is streamlined.

8 Conclusions

In this article, we have proposed a classification framework for multi-project planning environments, and we have pointed out that different levels of hierarchical decision-making (strategic, tactical and operational) require different methods and should not always be combined into one 'monolithic' model. The models should allow practitioners to better manage and control complex multi-project environments with uncertainty. We have also discussed the current state of the art in the research on hierarchical planning approaches, both for 'traditional' manufacturing organisations and for project environments. Some cases from practice have been included to illustrate the ideas that were put forward in this text.

Acknowledgments

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