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Research and Teaching Opportunities in Project Management

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Abstract One-fifth of the world's economic activity, with an annual value of $12 trillion, is organized using the business process of project management. This process has exhibited dramatic growth in business interest in recent years, with a greater than 1,000% increase in Project Management Institute membership since 1996. Contributing to this growth are many new applications of project management. These include IT implementations, research and development, software development, corporate change management, and new product and service development. However, the very different characteristics of these modern projects present new challenges. The partial resolution of these challenges within project management practice over the last 20 years defines numerous interesting opportunities for academic researchers. These research opportunities make use of a remarkably broad range of methodologies, including robust optimization, cooperative and noncooperative game theory, nonlinear optimization, predictive analytics, empirical studies, and behavioral modeling. Furthermore, the $4.5 trillion that is annually at risk from a shortage of skilled project managers, and the 15.7 million new jobs in project management expected by 2020 provide great opportunities for contributions to project management education. These educational opportunities include the integration of case studies, analytics challenges, online simulations, in-class games, self-assessment exercises, videos, and guest speaker presentations, which together form an appealing course for both business and engineering schools.

Keywords tutorial; project management; research opportunities; teaching opportunities

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1. Introduction

The business process known as project management has demonstrated remarkable growth in recent years, both in financial impact and in variety of applications. Regarding the financial impact of project management, today one-fifth of the world's economic activity, with an annual value of $12 trillion, is organized as projects (Project Management Institute [246]). Further evidence of the increasing influence of project management is provided by the growth in membership of the Project Management Institute, from about 50,000 members in 1996 to over 500,000 today. Few, if any, other business processes can demonstrate two consecutive decades of exponential growth in interest, or such a large professional interest level today. Meanwhile, the variety of project management applications has also expanded greatly, from an initial focus on construction and engineering applications, to encompass information technology, research and development, software development, pharmaceuticals, corporate change management, and new product and service development, among others. An important aspect of this outgrowth is that projects within these new application areas typically have very different characteristics from traditional projects, which fundamentally complicates project planning and execution. The need to address these complications has generated important methodological innovations within project management practice, which in turn motivates numerous interesting research challenges. Meanwhile, the rapid growth in project management applications has also created bottlenecks in the job market. For example, in summer 2010, according to various news sources, there were 10,000 unfilled jobs in information technology (IT) project management within Asia alone. Globally, the dramatic growth in project management applications is expected to generate 15.7 million new jobs in project management by 2020 (Project Management Institute [246]). This, in turn, is providing exciting opportunities for educational development within project management.

A *project* is conventionally defined as a "temporary endeavor undertaken to create a unique product or service" (Project Management Institute [245]). Alternatively, a project can be thought of as a well-defined set of tasks that must all be completed in order to meet the project's goals (Klastorin [170], Kerzner [168], Wysocki [326]). Several factors make the planning and execution of projects particularly challenging. The first is the uniqueness of a project. While it may be the case that individual component tasks are familiar and common to many projects, their overall combination and configuration at the project level is typically unique. While this uniqueness often makes the job of a project manager varied and interesting, it also limits the possibility of learning from economies of scale, as often happens in high-volume manufacturing. Second, in a typical project, many tasks are performed concurrently with each other. This presents difficulties in resource management, and frequently leads to multitasking, where a resource is shared across multiple tasks. Multitasking is difficult to manage efficiently and is often blamed for problems in executing projects efficiently (Goldratt [118]). Another key feature of projects is the existence of precedence relations between the tasks. These relations typically define constraints that require one task to be completed before another starts. This generates planning issues that are computationally intractable (Garey and Johnson [110]). Finally, risk is an important issue in many projects (Chapman and Ward [64]). The time-compressed nature of projects, and their frequent reliance on external resources such as subcontractors make them vulnerable to risks, some of which are not even foreseeable.

The three standard performance criteria in project management are completion of the project on time, on budget, and according to the agreed deliverables, or scope (Kerzner [168], Klastorin [170]). Yet many projects fail to meet these criteria, despite detailed planning before execution begins and the use of modern project management software. This comment applies even to traditional projects. However, the additional challenges and complications introduced by the nontraditional project management applications mentioned above has made failure to meet the performance criteria even more prevalent. As a result of these issues, project management appears to be a particularly difficult to manage business process, despite its recent massive growth in use. As we discuss, the substantial continuing challenges in project management are creating extremely interesting research and teaching opportunities. The purpose of this work is to outline what those opportunities are and provide some specific examples.

The remainder of this work is organized as follows. In Section 2, we provide a brief history of project management, document its dramatic recent growth, and discuss the new challenges presented by its greatly expanded set of applications. Section 3 summarizes the development of methodology for project management over time, from familiar techniques developed in the 1950s to more recent and newly influential ideas. In Section 4, we identify, and provide related literature for, many specific research opportunities in project management. In Section 5, we describe the benefits and challenges of teaching project management, propose some potentially useful approaches and course components, and suggest a course design. Section 6 provides a summary and concludes the work.

2. History and Growth

The use of project management as a business process goes back a long time. Indeed, the building of the Egyptian pyramids is believed by some to have been assisted by the use of simple project management principles. For much of the history of project management, the predominant application type was engineering and construction projects—for example, buildings, roads, and bridges. This was still the case when project management became formalized in the 1960s with the help of new software and computing power. A particularly impressive project management achievement at that time was the 1961–1969 Apollo moon landing project,[1] which required the coordination of about 410,000 workers at a cost of $25 billion in 1961 dollars, or equivalent to $195 billion in 2016. Another impressive achievement is the repeated organization of the Olympic Games using project management. This is an example of an event project, where the project deadline is fixed but there is typically some flexibility about the cost and scope.

Until recently, these successes were achieved for a fairly narrow range of applications. However, the potential for project management to be applied to a much wider set of applications gradually became apparent from the 1970s onward. Important modern applications include implementing a new information technology (IT) system; managing a research and development process; and managing strategic organizational change, pharmaceutical development, new product and service development, and software development. These new applications—for example, information technology—are among several reasons for the recent dramatic growth in the influence of project management. A second reason is shorter life cycles for products and services (Value Based Management.net [304]), which motivates the use of project management to bring new products and services to market more quickly than would otherwise be possible. A third reason is the effectiveness of project management in implementing organizational change, and in responding to newer technologies, more intense competition, and more demanding and less predictable customers (Kotelnikov [179]). A final reason is the need for flexibility, which has become an important component of modern project management methodology.

However, traditional and modern projects often have very different characteristics. First, the eventual configuration of traditional projects is much more transparent than for modern projects. For example, construction of a bridge or skyscraper typically does not start until very detailed blueprints have been developed and agreed. We say that such project management applications are *deterministic*. By contrast, the exact drug formula to be used in a new pharmaceutical is typically not known until late in the project, as a result of clinical trials and regulatory approval. Similarly, the exact configuration of a software code is not known until its last line is written and all bugs are removed. We say that such project management applications are *nondeterministic*. Since it is not possible to identify a complete list of tasks for nondeterministic projects before execution begins, the processes of scheduling, budgeting, and executing the project are considerably more difficult than for deterministic ones. A second difference lies in the difficulty of estimating the amount of work that has been completed so far. While a rough estimate of work completed is visually available in the case of a skyscraper, it is typically not available in the case of a software program. This lack of transparency about project progress makes it difficult to estimate time and cost variance relative to project progress. Without this information, it is more difficult to make efficient resource allocations or reallocations that ensure the performance of the project relative to its overall schedule and budget. A third difference lies in the time pressure under which projects are completed. By their nature, traditional projects are often of lengthy duration, whereas modern projects can be much shorter, especially for new products and services. With short product and service life cycles, for example, as in the consumer electronics industry, a delay in project completion can result in a product becoming uncompetitive. A fourth difference is in the relatively low level of understanding of the project on the part of users, particularly for IT projects. As a result, it is common for users to make last-minute scope changes—for example, requests for additional features or staff training—which would not be needed in traditional projects and which increase project completion time and cost.

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[1] *Wikipedia*, s.v. “Apollo program,” last modified August 1, 2016, https://en.wikipedia.org/wiki/Apollo_program.

All these characteristics of modern projects make them substantially harder to manage, and especially to complete on time, on budget and on scope, than traditional projects. As discussed in Section 3 below, this has resulted in the development of new project management methodologies that can more effectively manage modern projects.

There are several reasons for the increasing importance of project management as a business process. The main reasons are the following.

1. Project management effectively controls change, allowing organizations to introduce new products, processes, and programs.
2. Projects are becoming more complex, and thus more difficult to control, without a formal management structure.
3. Projects with substantially different characteristics, especially in IT, are emerging.
4. Project management helps cross-functional teams to become more effective.
5. Emerging project management methodologies are enabling a substantial broadening of project management applications.
6. Companies are using project management to develop and test their future leaders.

3. Development of Methodology

Although project management was not yet formalized as a business process at the time, a significant development occurred in 1917, when Henry L. Gantt (1861–1919) invented the Gantt chart. This chart keeps track of the progress of tasks and the allocation of resources to them over time, and it is the central tool for visualizing project progress when using standard project management software.

The critical path method (CPM) was developed by DuPont Company and Remington Rand in the late 1950s (Kelley and Walker [166]). This method plans projects without considering resources, costs, or uncertainty in task durations. These simplifications permit the use of a simple algorithm that delivers an optimal project schedule. Several project management software packages, including the market leader Microsoft Project, also use this method as a key step in developing solutions.

To estimate the effect of uncertainty in task times on project performance, Booz, Allen and Hamilton joined with Lockheed to develop the program evaluation and review technique (PERT) for a U.S. Department of Defense project, also in the late 1950s (Fazar [106], Malcolm et al. [202]). This technique enables estimation of the impact of uncertainty in individual task durations on the uncertain duration of the overall project. PERT is still used in many companies (White and Fortune [319]). However, PERT relies on several strong statistical assumptions that are difficult to justify for most projects. As a consequence, the project duration estimates obtained from PERT are often unreliable and on average substantially biased toward the low side. Schonberger [270] documents these problems. Hence, many companies develop their own adjustment factors to account for the bias in PERT. However, these factors tend not to perform robustly for a variety of projects.

An alternative to PERT is Monte Carlo simulation (Rubinstein and Kroese [258]). This methodology has been applied to project management since the 1960s and avoids the worst problems of PERT. However, it makes stringent requirements on the available data, since it requires knowledge of a probability distribution for each task time. In project management, the uniqueness of projects implies that such distributions are rarely available in practice. Furthermore, although they can be estimated, it is difficult to predict the effect of choosing an incorrect distribution on the overall project duration estimate. Another problem is that many companies have been reluctant to implement Monte Carlo simulation for project management, apparently because of unfamiliarity with its statistical justifications and also because of a possibly naïve satisfaction with their current methodology (White and Fortune [319]).

Earned value management (EVM) is an accounting and control system developed by the U.S. Department of Defense in 1962.[2] It is used to monitor the performance of projects during their execution, by adjusting the time spent and the cost incurred up to any point in time for the amount of progress made on the project. EVM has been used to support important decisions in defense contracting and is mandated for use in some defense contracts (Kwak and Anbari [183]). However, it has not been widely adopted by companies, partly because of difficulties in estimating the amount of work completed in nondeterministic projects. There are also concerns about whether it provides incentives that negatively affect project performance (Kim and Ballard [169]).

In recent years, there have been two significant methodological innovations in project management. First, critical chain project management (Goldratt [118]) was developed by the influential consultant and business writer Eliyahu M. Goldratt (1947–2011), in response to the perceived problems of traditional project planning methods described above. To prevent the dispersion of slack time around the project, where it may become lost as a result of Parkinson's Law (Parkinson [227]), slack time is collected into specific buffers. This converts the project management scheduling problem into one of buffer maintenance and management. As a result of the availability of software (for example, ProChain) to support critical chain project management, many companies have reported significantly improved project performance from using it (Patrick [228]).

Second, agile project management methodology was popularized by the Agile Manifesto (Agilemanifesto.org [8]), written by a group of eminent software developers. Agile principles include minimal planning and documentation, the submission of deliverables in small increments to obtain user feedback, and quick response to partial or prototype design. Relative to the traditional methodology of CPM and PERT, the amount of planning prior to execution is much less in agile. A project that is planned using agile methodology proceeds by iterations, each of which delivers a successively improved or enhanced prototype version of all or part of the project, for quick review and feedback by users. Agile project management has so far been influential mainly for the nondeterministic applications discussed in Section 2, especially software development. However, because it has some of the features of nondeterministic projects, the application area of new product and service development offers significant potential for future application of agile methodology (Smith [283]). A challenge that remains largely unsolved is the scaling of agile methodology for large projects, especially those outside of the software development domain.

4. Research Opportunities

Sections 4.1–4.15 describe various directions for research on project management. These directions are notable for the diversity of their research methodology, including robust optimization, real options analysis, nonlinear optimization, cooperative game theory, contract and mechanism design, economics, empirical studies, predictive analytics, and behavioral psychology. Each subsection contains specific suggestions for future research. These are designated by the format "[RQ$x.y$]," which denotes the yth research question in Section 4.x. The content of this section includes and extends the related discussions in Hall [129, 130]. Section 4.16 discusses the availability of data for project management research.

4.1. Project Expediting

4.1.1. Background. Three situations motivate the need to expedite, i.e., crash, the tasks in a project. The first is that, typically because of delays in previous tasks, the project is running behind schedule. The second is that, because of changed circumstances, the previous

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[2] *Wikipedia*, s.v. "Earned value management," last modified July 26, 2016, http://en.wikipedia.org/wiki/Earned_value_management.

schedule is no longer adequate for the commercial needs of the project. This situation occurs, for example, in a new product development project when a competitor unexpectedly releases a competing product. The third situation is that, because of modification of the project scope during the execution stage, the amount of work remaining in the project has increased. This situation occurs, for example, when unexpected rework is needed as a result of quality problems or when a project owner makes additional requests, i.e., "scope creep." In practice, crashing can be accomplished by a variety of means—for example, by overtime, by the application of additional resources, or by the subcontracting of tasks. A crashing decision typically represents a trade-off between time and cost (Kerzner [168], Klastorin [170]). When task times are known, this decision can be modeled as a simple linear program.

When task times are uncertain, however, crashing decisions become more complex and require estimation of uncertain task durations over the remainder of the project. Two standard approaches that are widely used to estimate project performance are PERT (Fazar [106], Malcolm et al. [202]) and Monte Carlo simulation (Rubinstein and Kroese [258]). Herroelen and Leus [148] provide a survey of different approaches to scheduling under uncertainty. Several works use stochastic analysis to make recommendations about crashing decisions. Bowman [42] applies infinitesimal perturbation analysis, based on simulation results, to construct a heuristic for making crashing decisions. Golenko-Ginzburg and Gonik [119] describe a zero-one integer program to prioritize activities. Golenko-Ginzburg and Gonik [120] apply a chance-constrained optimization model to control the project at discrete inspection points. Gutjahr et al. [125] develop a stochastic branch-and-bound approach based on sampling. Mitchell and Klastorin [208] design a heuristic to minimize the total of crash cost, expected makespan, and expected tardiness penalty costs. All these works assume full knowledge of the probability distributions of the arc lengths and also require independence of the task durations.

However, substantial evidence from both practice and academia (for example, Adler et al. [6], Cohen et al. [72], Leach [187], Herroelen and Leus [148], Pender [231], van Dorp and Duffey [305]) calls these two assumptions into question. Because of the uniqueness of projects, it is frequently the case that the project manager does not have an exact, or even approximate, probability distribution for the times of the individual tasks. Indeed, the project management literature assumes knowledge of only best, most likely, and worst times for the tasks. A further complication is that the uncertain task times may not be independent of each other. For example, if the same task operator or subcontractor performs two different tasks, it is likely that performance on those tasks is positively correlated. Hence, the estimation of remaining project performance is difficult.

Robust optimization (Bertsimas and Sim [35], Goh and Sim [116]) offers a way to find cost-effective crashing decisions without the need for the two potentially unreliable assumptions discussed above. This methodology can be used to develop linear decision rules that specify decisions based on information that is revealed over time. In the case of project management with uncertainty, task times are revealed over time, and that information is converted into crashing decisions. Because these techniques do not make strong distributional assumptions, their performance is typically more robust against unusual or extreme task time realizations. A related concept that may be useful is satisficing (Brown and Sim [49]). In evaluating the complex trade-offs between time, cost, and risk that are required for effective crashing decisions, satisficing models provide the advantage that they do not require the decision maker to specify, a priori, a risk aversion parameter.

Wiesemann et al. [320] consider a resource-constrained project management problem with uncertain task times. However, the task times can be reduced by the application of more resources. The objective is minimization of the worst-case project makespan. They describe procedures for finding upper and lower bounds on the optimal objective value that converge monotonically as the computation proceeds. A computational study for projects with up to

300 tasks demonstrates the effectiveness of the proposed procedure. The procedure is most effective when the resource budget is large and the uncertainty budget is small.

Goh and Hall [115] consider projects with activity times from a partially specified distribution within a family of distributions. This family is described by one or more of the following: support, mean, and covariance. The objective considered is total completion time penalty plus crashing and overhead costs, using a robust optimization model with a conditional value-at-risk satisficing measure. Decision rules are developed for activity start time and crashing decisions. Computational studies show that, relative to PERT and Monte Carlo approaches, the robust crashing policies provide both a higher level of performance, i.e., higher success rates and lower budget overruns, and substantial robustness to activity time distributions.

4.1.2. Future Research. Several opportunities exist for additional research related to the expediting of projects, as we now discuss.

[RQ1.1] Is it possible to use robust optimization to model discrete crashing resources?

[RQ1.2] Is it possible to use robust optimization to model discrete penalty functions for project completion time, such as arise in large public construction projects (Philips [233])?

[RQ1.3] Especially for IT projects, where loss of resources during project execution seems to be worse than in other application areas, is it possible to use robust optimization to model uncertainty about the availability of resources for crashing?

[RQ1.4] More generally, the study of multiple projects that share crashing resources would be a valuable contribution.

[RQ1.5] An alternative to crashing is fast tracking (Kerzner [168]), which involves limited concurrent processing of tasks that formally have a precedence relationship. Fast tracking imposes indirect costs on a project, and trade-offs with crashing options deserve formal investigation.

4.2. Project Selection

4.2.1. Background. Both statistical and informal evidence suggest that successful project management depends on selection of the right projects (Cooper et al. [75]). This is because well-chosen projects are typically easy to manage, whereas poorly chosen projects not only underperform but also take resources away from other projects. Chien [67] and Heidenberger and Stummer [141] provide reviews of the project selection literature.

Project selection can be performed in two fundamentally different ways. First, projects can be selected individually, typically by initially using benchmarks to filter out some projects and then using a combination of quantitative and qualitative measures to evaluate the remaining projects in more detail. In many organizations, available projects are initially screened according to various criteria such as their payback period and risk characteristics. Projects that pass initial screening are subjected to a more detailed scoring and/or ranking analysis. Nelson [217] provides a scoring model for selecting flexible manufacturing system projects. Lu et al. [196] study sequential project evaluation for dynamically arriving projects. Henriksen and Traynor [144] describe a scoring model for selecting research and development projects. Meade and Presley [206] describe a multifactor ranking process that considers an organization's strategic objectives and culture. Poh et al. [238] provide a comparison of project selection methods that use the analytic hierarchy process (Saaty and Peniwati [262][3]).

Second, simultaneous decisions can be made about accepting multiple projects, which defines a project portfolio planning approach. This approach provides control of risk through diversification, better resource utilization, the potential to model dependency between

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[3] See also *Wikipedia*, s.v. "Analytic hierarchy process," last modified June 22, 2016, https://en.wikipedia.org/wiki/Analytic_hierarchy_process

projects, and optimization of overall portfolio performance. If project returns are deterministic, a natural approach is the use of knapsack (Kellerer et al. [165]) and related models (Dickinson et al. [87], Fox et al. [109]). Although this approach works most easily when choosing between a known set of projects, it can also be applied in environments with newly arriving projects, by retaining some budget for potentially arriving projects.

However, project portfolio planning is much more complex in the presence of (a) uncertain project returns without well-specified probability distributions; (b) interactions, such as synergistic value, between project returns; and (c) correlation between project returns—for example, between projects within the same industry or locality. In many practical project selection problems, there is a high level of uncertainty in project returns (Pohl and Mihaljek [239]). This uncertainty arises regarding its technical success or its commercial success (MacMillan and McGrath [201]). Technical uncertainty arises from uncertain outcomes in research and development (e.g., for new products), in prototype testing (e.g., for safety testing of automobiles), and in regulatory approval (e.g., for new pharmaceutical products). Commercial uncertainty arises from randomness in time to market (e.g., for seasonal products such as fashion items and toys), in the introduction of competitors' products (e.g., for consumer electronics), and in economic factors (e.g., a recession). Henig [143] models a project selection problem with uncertain returns as a stochastic knapsack problem, with the objective of maximizing the probability of attaining a given target for total return. Kleywegt and Papastavrou [171] extend the literature of the stochastic knapsack problem by considering items, i.e., projects, that arrive according to a Poisson process, with uncertain resource requirements and rewards. They provide optimal recursive and closed-form solutions for various cases. Other optimization approaches besides those based on the knapsack problem are also studied. Loch and Kavadias [195] consider the problem of dynamically adjusting investment levels in programs or projects, resulting in higher or lower returns, using the concept of marginal returns to investment. Carlsson et al. [57] develop a fuzzy mixed integer programming model and incorporate the value of managerial flexibility by using real options (see Section 4.3). Their problem includes only a single budget constraint.

Approaches from financial portfolio theory include (a) the maximization of expected return, (b) the minimization of the probability of underperformance relative to a given target, (c) the minimization of variance subject to a target expected return (Markowitz [204]), and (d) the maximization of the safety-first ratio (Roy [257]). The work of Aumann and Serrano [19]) on riskiness indices motivates the use of choices based on targets. For example, it should be possible to identify the least risky project portfolio that achieves a given target in a certainty-equivalent sense. However, doing so presents computational challenges.

Hassanzadeh et al. [137] develop a multiobjective binary integer programming model for research and development (R&D) project portfolio selection with competing objectives, when the data in both the objective functions and constraints are uncertain. They apply robust optimization to deal with the uncertainty and an interactive procedure to evaluate trade-offs between the objectives. Robust nondominated solutions are found by solving the linearized version of a robust augmented Chebyshev program.

Hall et al. [134] consider a project selection problem where each project has an uncertain return with partially characterized probability distribution. The objective is to minimize the underperformance risk of the project portfolio relative to a target. The model includes correlation and interaction effects such as synergies, and it is solved using binary search, with the solution of the subproblems from Benders decomposition techniques. The project portfolios generated by minimizing the underperformance risk are more than competitive in achieving the target with those found by the classical finance portfolio optimization approaches mentioned above.

4.2.2. Future Research. Opportunities exist to use robust optimization for additional problems related to project selection, as we now discuss.

[**RQ2.1**] Regarding project portfolio optimization, the effect of uncertainty about available budgets (Koç et al. [174]) and other resources should be considered.

[**RQ2.2**] Robust optimization should also be applied to dynamic project selection problems, where projects with uncertain initial investment cost and return become available over time (Herbots et al. [145]).

[**RQ2.3**] Robust optimization can be applied to the problem of selecting projects as they arrive dynamically, as a result of which some available resources need to be retained for new potentially arriving projects.

[**RQ2.4**] It would be valuable to identify patterns of correlation that occur in the returns of different projects for particular project management applications, and model that correlation into an optimal project selection approach. An example would be projects that develop similar products for the same consumer market.

[**RQ2.5**] Finally, the project selection problem discussed above can be generalized to allow for decisions about the relative timing of multiple projects, given the need to match resource requirements and resource availability over time; target-based robust optimization can also be applied in this case.

4.3. Real Options Analysis

4.3.1. Background. Real options analysis (ROA) can be used to apply option valuation methods from finance to the evaluation of projects.[4] In this context, a real option is the right, but not the requirement, to make a managerial decision that affects the performance of a project. Yeo and Qiu [332] identify seven management options that are compatible with the logic of real options: growth, staging, deferment, exit, sourcing, scope, and learning. The theory underlying real options was developed by Dixit and Pindyck [89] and Trigeorgis [300]. An introduction to the use of real options for investment decisions, including project selection, is given by Amram and Kulatilaka [14]. A practical guide to the use of ROA for project valuation is provided by Kodukula and Papudesu [175]. Boute et al. [41] present a tutorial about the application of ROA to project management. They provide an example that compares three valuation approaches: net present value (NPV), decision trees, and ROA. Real options have been successfully used for evaluation of some projects but not without concerns and resistance, as we now discuss.

Benaroch et al. [33] conduct an empirical study of whether project risk managers follow the logic of option-based risk for 15 IT investments under consideration at an Irish financial services company. Their results suggest that the managers do so, but based mainly on intuition. They argue that greater consistency of effective risk management could be achieved by the use of formal real options models. Their work also reveals two practical shortcomings of ROA. The first is that it cannot be used for all types of risk mitigation. The second is that managers have difficulty in fitting ROA concepts into their decision processes.

There are some apparently successful applications of ROA. Zhu [337] applies a real options approach to the investment evaluation of nuclear power projects. These projects are difficult to evaluate because of substantial uncertainties, especially with respect to technology, nuclear generating cost, radioactive leakage, and prices. An ROA model that uses Monte Carlo simulation to represent these uncertainties is developed and applied to two case studies. Chang [62] discusses the problem of evaluating renewable energy projects. Three important recent advances are critically reviewed: the systematic use of financial risk management instruments, the integration of ROA techniques, and incorporation of the logic of ROA into decision analysis and system dynamics frameworks. Potential deficiencies of these approaches—specifically, behavioral uncertainty and the danger of contract breakup—are

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[4] *Wikipedia*, s.v. “Real options valuation,” last modified July 31, 2016, https://en.wikipedia.org/wiki/Real_options_valuation.

also identified. The paper addresses these two problems by incorporating the concept of risk-bearing capacity into an NPV framework. Chen et al. [66] develop an approach to evaluate IT projects that are subject to multiple risks, and they implement it for an enterprise resource planning project at a construction company.

However, there are incompatibilities between the theoretical justification for ROA and the application area of project management. Wang and Halal [314] criticize the use of ROA for project management, since it relies on modeling assumptions from finance that are not necessarily satisfied. For example, Trigeorgis [300] indicates that either the underlying asset distribution must be mimicked by a financial security that serves as a replicating asset or the market must be complete in the sense that any real asset can be replicated from an equivalent portfolio of traded securities. Regarding the first alternative condition, Wang and Halal [314] argue that the return of a project depends on many factors specific to the industry and the project itself, and furthermore, projects are relatively short-lived. This last point compromises the required "no arbitrage" assumption. Regarding the second alternative condition, they argue that monopoly elements enable some firms to earn routinely excessive returns that are not available to investors in financial markets. Their overall perspective is that the risks of real asset investment are different from those that affect financial securities.

Hartmann and Hassan [136] conduct a survey about the use of ROA in pharmaceutical development projects. They find that adoption of ROA techniques is significantly lower in pharmaceutical companies than in financial services companies: 12% of companies use ROA in preclinical evaluation and up to 26% use it in various phases of clinical trials. They also document resistance to the use of ROA on account of its complexity and its lack of credibility with decision makers. Garvin and Ford [111] develop six explanations for the lack of implementation of ROA in infrastructure projects. For example, they report evidence that project managers are risk averse in valuing real options, that option values are decreased by manipulation of the values of underlying assets, and also that project managers do not have the resources to exploit real options fully.

Additional concerns are raised by Huchzermeier and Loch [153], who observe that project managers face several types of uncertainty, not only uncertainty in returns as is the case with financial options. Specifically, projects are complicated by uncertainty in project budgets, project performance, and commercial factors that affect the end product. As a result of these factors, if uncertainty is revealed after decisions have been made, greater variability may reduce the value of options. Furthermore, greater variability may be associated with a lower probability that an option will ever be exercised. These arguments lead to the counterintuitive result that higher risk may reduce the value of real options.

A further concern is that ROA is not of practical use if a company lacks a mechanism to implement a management option. For example, ROA author Nalin Kulatilaka is quoted as saying that "you can make any project look good if you build in enough options," but "a real-world approach must address two questions: when exactly do you shut it down, and is there a good mechanism in sight to do that?" (Fink [107]). A related research study by Adner and Levinthal [7] supports the view that organizational processes create problems in using ROA. For example, they argue that effective management of real options requires a rigid decision-making structure, and the more open-ended initiatives are, the more problematic it is to use real options. Despite these concerns, it is still the case that many organizations wish to apply ROA for project risk management, which makes it a relevant research topic.

4.3.2. Future Research. As the above discussion makes clear, the application of ROA to project evaluation is hitherto not a story of unqualified success. There are several issues that need to be resolved if this methodology is to deliver high impact and value in a variety of project management applications.

[**RQ3.1**] Is it possible to develop a better understanding of project risk and how its differences from financial risk affect the use of ROA, as discussed by Huchzermeier and Loch [153]?

[RQ3.2] Is it possible to identify project management applications where the conditions of either a replicating asset or a complete market are satisfied; alternatively, is it possible to estimate by how much deficiencies in those assumptions compromise results obtained by ROA?

[RQ3.3] Is it possible to identify examples of success and failure for ROA methodology outside of pharmaceutical development and understand where and why resistance to its use by decision makers occurs?

[RQ3.4] As suggested by Boute et al. [41], is it possible to apply ROA to problems with arriving projects that have unknown resource requirements, to compare proactive and reactive scheduling approaches, and to model cancellation decisions in the presence of unforeseen events?

[RQ3.5] The explanations of Garvin and Ford [111] for the lack of ROA use are developed for infrastructure projects; however, it would be valuable to study their relevance, or develop alternative explanations, for other project management applications.

4.4. Maximization of Risk-Adjusted NPV

4.4.1. Background. One of the most widely used measures for evaluating a project is the NPV of its cash flows (Remer and Nieto [256]). By considering the time value of money, a company can compare the value of investing in a project with the value of alternative investments. Beaves [31] discusses the limitations of conventional NPV formulas and the need for a generalized NPV formula. Haley and Goldberg [128] consider the issue of whether emphasizing NPV in the analysis and selection of new product research projects hinders innovation as a result of short-term biases. Hodder and Riggs [150] describe several pitfalls that arise in the overinterpretation of NPV analysis for project evaluation. Archer and Ghasemzadeh [17] describe an integrated framework for project portfolio selection using NPV. Several authors use NPV analysis for evaluating and selecting projects for specific applications. These include Cooper et al. [76] for new product selection, Nelson [217] for manufacturing modernization projects, Oral et al. [224] for project selection problems with competing interests among multiple stakeholders, and Kolisch and Meyer [176] for pharmaceutical development projects.

Given the timing of all the tasks, the NPV of a project can be calculated easily. However, there is typically substantial flexibility in the timing of the noncritical tasks that can be used to increase the NPV without delaying the project. As a result of precedence relationships between the tasks, the decisions about the timings of the tasks are connected. This complicates the problem of finding the timing of the tasks that maximizes the NPV. Szmerekovsky [292] discusses this problem from the viewpoint of both the project owner and the project company maximizing their NPV. This problem has been studied under the assumption of a constant discount rate. For example, if q_i denotes a cash flow for tasks $i = 1, \ldots, n$, T_i the time when it occurs, and α the project discount rate, then the present value of a schedule of an n task project is $\sum_{i=1}^{n} q_i e^{-\alpha T_i}$. Russell [259] models this problem as a nonlinear program with linear constraints and a nonconcave objective. However, Grinold [124] shows that this problem can be solved efficiently using results from tree networks. Russell [260] compares six heuristic scheduling rules for a generalization of this problem that includes resource constraints. Elmaghraby and Herroelen [99] provide a critical review of the research literature on maximizing the NPV of a project by timing decisions. Their main criticism is the typical assumption that the cash flow at the end of a task is independent of its time, which is inconsistent with penalty clauses in some project contracts. They also provide a solution procedure that is apparently simpler than those of Russell [259] and Grinold [124]. Computational experience with this procedure is reported by Herroelen and Gallens [146].

Doersch and Patterson [93] use a zero-one integer programming model to solve the problem of maximizing NPV, subject to capital rationing constraints. Yang et al. [328] develop a similar model to maximize NPV, subject to resource limitations that vary over time. Icmeli and Erenguc [157] and Vanhoucke et al. [312] study the problem of maximizing NPV subject to resource constraints, and they develop branch-and-bound algorithms for small projects. Schwindt and Zimmermann [272] consider the maximization of project NPV subject to general constraints, and they describe a steepest ascent procedure. Etgar et al. [104] address the criticism of Elmaghraby and Herroelen [99] by allowing the cash flow of a task to depend on its completion time. They use simulated annealing to solve this problem heuristically for projects with up to 45 events. Etgar and Shtub [103] consider a special case of the previous problem where a task's cash flow is a linear function of the completion time of the task. They provide a simple, optimal algorithm to maximize NPV but no computational results. For the same problem, Vanhoucke et al. [311] provide a more complex procedure that includes dominance rules and other computational enhancements, and they find optimal solutions for projects with up to 120 tasks. Vanhoucke et al. [313] describe a branch-and-bound algorithm that computes upper bounds by making piecewise linear overestimations and report results for projects with up to 50 tasks.

Chapman and Ward [64] provide a discussion of project risk. Project risk arises from uncertainty about its technical and commercial success (MacMillan and McGrath [201]). Technical uncertainty arises, for example, from uncertain outcomes in research and development, prototype testing, and regulatory approval. Commercial uncertainty arises, for example, from randomness in time to market, the introduction of competitors' products, and general economic factors. Risk is typically considered as a component in discount rates.[5] However, the use of a conventional NPV measure based on constant discount rates over time is problematic in the many projects where the risk level declines over time. An example arises in the development of new pharmaceuticals. As each stage of testing, animal trials, clinical trials, and regulatory approval, is passed, the risk level of the project declines significantly. Myers and Shyam-Sunder [212] document that risk is higher in early-stage pharmaceutical development projects than in mature ones. The following comments from the business community document similar observations in diverse project management applications:

— "As progress is made through the stages, project risk reduces as more certainty and information becomes available" (East Hampshire District Council [95], p. 28).

— "…[D]uring project execution, risk progressively falls to lower levels as remaining unknowns are translated into knowns" (Stanleigh [285]).

— "As the project progresses and more information becomes available to the project team, the total risk on the project typically reduces, as activities are performed without loss" (Project Management for Instructional Designers [244]).

Where a project has its own unique risk structure, its discount rate should reflect its risk level (*Investopedia* [158]). Therefore, based on the above comments, the discount rate should decline during project execution. However, the standard approach of using the capital asset pricing model is not recommended, since the critique of Fama and French [105] identifies several requirements that unique projects do not meet; for example, variance of returns is not an adequate measure of risk in projects.

From the above discussion, as most projects are executed, the meeting of various challenges embodied in the tasks, and the passing of various reviews and tests, lowers the amount of risk in the project. Hall et al. [133] model the monotonically nonincreasing risk level in the project by reducing the project discount rate, whenever a task is completed, by a prespecified amount that depends on the task. For example, project risk reduces by a larger amount when a task that associates strongly with major risks to the project is completed than when other tasks are completed. However, modeling the project discount rate in this way introduces additional mathematical complexity into the problem, because the discount rate becomes a function of the decisions about the timing of the tasks. Hence, the objective function of

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[5] *Wikipedia*, s.v. "Cost of capital," last modified April 22, 2016, https://en.wikipedia.org/wiki/Cost_of_capital.

maximizing the NPV by timing decisions becomes nonlinear and nonconcave, which limits the size of problem instance that can be solved. While this problem is computationally challenging, it is important to solve it, since the assumption of a constant discount rate in the existing literature is unrealistic for many projects.

4.4.2. Future Research. There are several valuable research issues related to the development of maximization of risk-adjusted project NPV, as we now discuss.

[RQ4.1] Is it possible to obtain a more accurate understanding of how risk evolves over the duration of a project, either in general or for particular project management application areas?

[RQ4.2] Is it possible to model and solve this problem with risk effects that are more general than linear additive functions over the tasks? For example, there may be a small risk associated with each of two tasks, but their combined risk may be large.

[RQ4.3] Since the models that are required to consider risk-adjusted maximization of NPV are nonlinear and nonconcave, and hence highly intractable, simpler heuristic approaches should also be developed for practical use.

[RQ4.4] Szmerekovsky [292] considers a project where the client selects the payment activities and the contractor selects the activity schedule, each to maximize his own NPV. This problem can be generalized to allow for risk-adjusted NPV.

[RQ4.5] Project managers typically classify the risks they face into two categories, "known unknowns" and "unknown unknowns." How to adjust project risk and discount rates to allow for the latter type of risk is a difficult challenge.

4.5. Cooperation and Contracting

4.5.1. Background. Several issues arise in connection with the planning and scheduling of resource constrained projects. Overviews of the related research literature are provided by Demeulemeester and Herroelen [82], Herroelen et al. [149], and Brucker et al. [52]. These works document the intractability of the resource-constrained project scheduling problem and discuss various approaches to solving it. Most of this literature considers the prime contractor or project owner as a single decision maker who owns all the necessary resources and controls all the tasks. For example, scheduling decisions that involve expediting, or crashing, the individual tasks are made by a sole decision maker to optimize some overall time and cost objective for the project. However, this perspective ignores the necessity of *outsourcing*, which is the procurement of products or services from external subcontractors. Since at least the early 1990s, firms have increasingly outsourced activities (Pralahad and Hamel [242], Quinn and Hilmer [249], Tully [302]). The outsourced activities range widely and include specialized tasks performed by outside subcontractors. These realities necessitate the coordination of projects across organizational boundaries (Amaral et al. [11]).

Although the subcontractors are independent agents, they frequently cooperate with each other in practice to work efficiently. If they cooperate, then they share their resources and also coordinate their schedules to perform the tasks, for mutual benefit. The subcontractors' coordination problem can be modeled as a cooperative game (Peleg and Sudhölter [230]). There are several previous studies that apply cooperative game concepts to project management. Bergantiños and Sánchez [34] consider a project that experiences a delay in completion time. The identification of which tasks have caused the delay suggests how the cost of compensation to the client should be divided among the tasks. Brânzei et al. [44] describe an approach based on an optimistic and a pessimistic game, and a second approach based on a serial cost-sharing rule. The latter approach is extended to a weighted serial cost sharing rule by Castro et al. [61]. Both the two previous studies assume that the project is inevitably delayed. Estévez-Fernández et al. [101] study an expedited *project game* where tasks cannot be delayed. This game is shown to be convex. The authors also consider another project game where some tasks are delayed and other are expedited. Assuming that the delayable tasks are indeed delayed and the expeditable tasks outside the coalition are completed on time, this game is convex. Castro et al. [60] also consider a project game where the characteristic function for a given subset of activities represents the amount of expediting that these activities induce in the project, and they show that this game is balanced.

This problem can alternatively be modeled within the principal–agent framework,[6] which concerns difficulties in motivating the agent (subcontractor) to act in the best interests of the principal (the prime contractor). This classification is based on different objectives between the two parties, instead of asymmetric information, in our problem. Rather, all parties face significant uncertainty. This perspective is supported by, for example, Tadelis and Bajari [294], who comment, "…[S]cholars and practitioners of engineering and construction management argue that the central problem in procurement is not that suppliers know so much more than procurers at the onset of the project, but that instead both procurers and suppliers share uncertainty … " Models of different objectives between the principal and the agents under symmetric information are common in the principal–agent literature (Jaffe and Stavins [159]). A cooperative coalition of subcontractors can be formed from an existing network of available project subcontractors. Examples of such networks include the Global Projects Network [113] and ACES Global Quality and Services [4]. The main advantages of such networks include improved quality control, customer coverage, and improved information sharing (CaliforniaFIRST [54]). Hyun [156] studies subcontractor partnerships in European automobile manufacturing and concludes, "As the competitiveness of the company is not determined by the company itself, but by its supplier network, partnership commitments and effective supplier management become very important" (p. 66). Errasti et al. [100] conduct an empirical study of subcontractor partnerships in the construction industry. They comment, "Generally, main subcontractors and subcontractors, operate within a project based system with the result that these organizations are increasingly developing horizontal and integrated organizational structures, which are geared toward the management of projects" (p. 251). Albino et al. [10] discuss examples of horizontal cooperation to minimize unsatisfied demand. Perng et al. [232] discuss the potential benefits of subcontractor cooperation in the construction industry and how those benefits can be distributed among the participants using concepts from cooperative game theory.

A natural generalization of this problem allows for *milestone* payments, such as frequently occur in projects that are expensive or of long duration. For example, in the construction industry, the U.S. Department of Transportation [273] summarizes this feature of projects: "Milestone payments or incentives are given to a contractor for completing a pre-determined milestone, on or ahead of schedule. Likewise, a disincentive can be incurred per day for failure to hit the target completion date." Milestone payments are also well recognized and modeled within the academic literature (Abu-Hiljeh and Ibbs [3], Vanhoucke et al. [312]).

Cai et al. [53] consider a project management problem where the prime contractor outsources tasks to subcontractors. Achieving an optimal solution for the project requires coordination among the subcontractors and contract design to incentivize them. By modeling the subcontractors' coordination problem as a cooperative game, they design a profit-sharing scheme under which the subcontractors cooperate. Two contract designs are considered: a uniform contract across all subcontractors and a nonuniform one that customizes incentives for each subcontractor, and efficient algorithms are developed to solve implicit optimization problems for the optimal contract parameters. The pooling effect of subcontractors' cooperation mitigates the negative impact of poor estimates. Three apparently counterintuitive results include the following: (i) the subcontractors' profits may decrease if they provide false information, (ii) it is safer for the prime contractor to overestimate subcontractors' crashing costs than to underestimate them, and (iii) uniform contracts often deliver more project profit than nonuniform ones.

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[6] *Wikipedia*, s.v. "Principal-agent problem," last modified April 12, 2016, https://en.wikipedia.org/wiki/Principal%E2%80%93agent_problem.

4.5.2. Future Research. There are several valuable research issues related to the maximization of risk-adjusted project NPV, as we now discuss.

[RQ5.1] Besides the problem of finding an allocation in the core, which is considered in several of the works discussed above, it is also valuable to address the problem of checking whether a given profit distribution is in the core or not. Solving this problem would facilitate negotiations among the subcontractors.

[RQ5.2] The works discussed above consider crashing costs that are linear; hence it would be valuable to consider more general costs. A practical example is piecewise linear and convex crashing costs. The study of projects with discrete crashing cost functions would be more challenging.

[RQ5.3] There are other cooperative concepts that can provide additional understanding of cooperation within project management; these concepts include the Shapley value (Shapley [276]), the kernel (Davis and Maschler [80]), and the nucleolus (Schmeidler [269]).

[RQ5.4] Research in this area should be extended to consider issues of resource sharing and cooperation across multiple projects.

[RQ5.5] The properties of different contracting schemes for project management should be investigated.

4.6. Early Task Completion Incentives

4.6.1. Background. Demeulemeester and Herroelen [82], Herroelen et al. [149], and Brucker et al. [52] document the intractability of the resource-constrained project scheduling problem, and each discusses various approaches to solving it. Most of this literature considers the prime contractor or project owner as a single decision maker who owns all the necessary resources and controls all the tasks. In practice, however, both task operators who are internal to the project organization and outside subcontractors need incentives to perform in a way that supports optimal project performance. Outsourced activities range from back-office business processes such as payroll processing (Thomas and Thomas [298]), to the manufacturing of components or entire products (Sturgeon [290]), to core activities related to new product development (Pisano and Verganti [237]). Furthermore, in many projects, it is essential that some tasks require the specialized expertise of outside subcontractors.

Task times in projects are typically uncertain and may be either longer or shorter than their original estimate or their expected value. Problematically, however, the effect of this uncertainty on project completion time is not symmetric. Task times that are longer than expected typically increase project completion time, whereas task times that are shorter than expected fail to reduce project completion time. The latter effect is primarily due to the behavioral phenomenon known as Parkinson's law (Parkinson [227]). This well-known principle states that "work expands to fit the time available." An equivalent statement for project management is that the time that it takes to complete a task is the amount of time that is made available for it. The principal causes of Parkinson's law are overestimating the importance of the task, lack of focus, lack of urgency, general procrastination, an unnecessary obsession with small quality details, and anxiety about being allowed less time for the task in future (Chen et al. [65]). As a result of Parkinson's law, tasks that are completed early are not delivered to the project until their due date, which is defined, for example, by a late finish time under critical path method planning. Critical chain project management (CCPM) (Goldratt [118]) is designed in part to resolve the problem of Parkinson's law. Patrick [228] provides a detailed and supportive discussion of CCPM. However, Raz et al. [254] identify concerns about the behavioral effects of reducing safety margins and also about the relative lack of progress control that arises from the removal of task deadlines under CCPM.

An alternative resolution of Parkinson's law would be an incentive compatible mechanism (Hurwicz [155]) for the agents, i.e., the task operators or subcontractors. For example, agents who deliver a task early should receive a carefully calculated bonus. A mechanism is incentive compatible if it is each agent's optimal choice, irrespective of what other agents do. Myerson [213] shows that any equilibrium outcome of an arbitrary mechanism can be replicated by an incentive-compatible direct mechanism. This is the revelation principle, which simplifies the search for an efficient mechanism. What is needed to resolve Parkinson's law is an incentive system that encourages task operators to report early completion of their tasks and allocates rewards for doing so with sufficient flexibility that various considerations, such as reserving a sufficient return for the project manager and meeting the available budget, are respected. The design of such a scheme becomes substantially more complex if a single task operator has control over multiple tasks, and moreover, those tasks are mutually dependent—for example, if some are successors of others.

Wu et al. [325] identify an important behavioral factor in project performance, which they term cost salience. This factor causes project team members to view the cost of immediate effort as greater than the cost of future effort. The leads to procrastination during the early part of the project execution and overwork during the later stages, which in turn results in delays in project delivery and also loss of quality. Traditional analysis of incentives in project management focuses incentives on the later stages of the project. However, the authors conclude that, as a result of cost salience, incentives should be focused on the early stages of a project, where they are needed more and can also be more effective.

In large projects, it also necessary to design incentives into *milestone* payments. In projects that are expensive or of long duration, it is common for subcontractors to receive milestone payments. Practical examples occur most frequently within the construction and pharmaceutical industries (U.S. Department of Transportation [273]). In the pharmaceutical industry, examples of substantial milestone payments are provided by the *San Diego Business Journal* [266] for Isis Pharmaceuticals and by the *Wall Street Journal* [297] for the Sucampo Corporation. Milestone payments are also well recognized and modeled within the academic literature (Abu-Hiljeh and Ibbs [3], Shtub and Etgar [281]).

Chen et al. [65] describe an incentive-compatible mechanism to resolve Parkinson's law for projects planned under CPM and under CCPM. The incentive payments received by all task owners under CCPM weakly dominate those under CPM; moreover, the minimum guaranteed payment to the project manager remains unchanged. This work also develops an incentive-compatible mechanism for repeated projects, where commitments to early completion continue for subsequent projects; hence, there may be differences between short-run and long-run incentives. The proposed schemes are also group-strategy-proof.

4.6.2. Future Research. Several interesting problems remain open for future research with respect to incentives for early task completion.

[RQ6.1] It would be useful to study incentives that involve time/cost trade-offs that are implied, for example, by the possibility of crashing tasks.

[RQ6.2] The interaction between incentive design and the decision to outsource particular tasks is an important one, especially for projects with a high technical requirement.

[RQ6.3] Incentive-compatible mechanisms should be developed for other project management control structures, e.g., agile (Agilemanifesto.org [8]).

[RQ6.4] In practice, the effectiveness of incentive schemes may be different between employees who are internal to the project organization and external subcontractors. An empirical study should be conducted to test whether such differences exist in order to design more effective incentive schemes.

[RQ6.5] An empirical study to evaluate the effectiveness of CCPM (Goldratt [118]) at resolving Parkinson's law, and to identify what are the organizational and project factors that make it more or less effective, would be highly valuable.

[RQ6.6] For employment systems where bonus payments are typically not made for individual work assignments, alternative forms of incentive to resolve Parkinson's law need to be developed.

4.7. Estimation of Project Completion Time

4.7.1. Background. Accurate estimation of project completion time, or makespan, has a large economic value to companies. An estimate that is too low may result in expensive crashing, a disappointed project owner, and possibly contract penalties. Conversely, an estimate that is too high may result in less than competitive bidding and the loss of a contract. The standard methodology for estimating the distribution of task times is PERT (Fazar [106], Malcolm et al. [202]). However, as a result of ignoring merging paths in the project network, PERT overestimates the probability of completing the project by any given time and thus, for example, underestimates the expected makespan. This error in PERT is called the *merge bias*, which can be substantial (Hartley and Wortham [135], Klingel [172], Mummolo [211], Schonberger [270], Welsh [316]). Another problematic assumption of PERT is that task durations are probabilistically independent.

Several works attempt to compensate for the merge bias in PERT by studying information that is found either from the merging process in the project network or from a sample of potentially longest paths. Gong and Hugsted [122] develop a heuristic estimation procedure; when two or more paths merge at an event, a formula based on cumulative probability functions is used to estimate the expected value and variance of the corresponding event time. Gong and Rowings [123] extend that work to calculate a safe float that can be used to adjust PERT estimates of project completion time. Banerjee and Paul [28] study the effect on the size of the merge bias of (a) tasks with correlated durations (for example, if they are performed by the same contractor) and (b) paths with tasks in common. Jun and El-Rayes [162] consider all possible path lengths in the project but enumerate only those that are more critical, by identifying and removing paths that are highly correlated or have a high probability of completion by a given deadline. For a construction project with 971 tasks, they find results that are within 3% of those found by Monte Carlo simulation.

A more mathematical line of research attempts to bound the distribution of the makespan. Hagstrom [127] shows that the problem of computing the probability that a project completes by a given time is #P-complete (Garey and Johnson [110]). Anklesaria and Drezner [15] develop a multivariate approach for estimating the makespan, which allows for correlation between task time durations. Their method chooses a small number of paths that are stochastically dominant with respect to parametrically varied values of the makespan. Sculli and Shum [274] model the makespan as the maximum of a set of variables, i.e., path lengths, with a multivariate normal distribution. Their methodology relies on the assumption that the maximum of two normally distributed random variables is also normally distributed. For two small projects, they achieve bounds of less than 0.3%, relative to simulation. Möhring [209] provides a detailed review of work that bounds the probability distribution of the project makespan under uncertain activity times. Ludwig et al. [198] conduct an extensive computational study of several different bounding techniques, using networks with up to 1,200 tasks, a variety of different distributions, and comparisons with simulation using up to 1.5 million realizations. They find that a method of Spelde [284] that uses only the $n/3$ longest paths in an n project network, as identified by a variant of an algorithm of Dodin [91], delivers bounds with average relative errors of between 1.6% and 2.6% relative to simulation results. Ludwig et al. [198] extend this methodology to estimate any quantile of the distribution of the project makespan, and they conclude that Spelde's method dominates others with respect to running time and the accuracy of its estimates.

Bertsimas et al. [36] use semidefinite programming to find tight bounds for several combinatorial optimization problems. For the project makespan problem, they describe a computationally tractable method to find the worst-case expected tardiness, under information about the first three moments of the task time distributions. Doan and Natarajan [90] develop an efficient procedure for computing a tight multivariate marginal upper bound on expected project duration under two special cases of task time durations: where durations are scenario representable and where they are discrete. Zheng et al. [336] show that the least squares normal approximation of the random project completion time can be estimated from a solution to the persistency problem studied by Bertsimas et al. [37]. This estimate is then improved by a least squares quadratic estimator. For random networks with up to 44 tasks, this procedure routinely estimates the project completion time with small errors, even when correlations between task durations are large. For a review of moment-based persistency models, see Li et al. [192].

The *criticality* of a task is the probability that it is critical in the realized project network (Klastorin [170]). The information contained in criticality indices is used to prioritize resource allocations. Dodin and Elmaghraby [92] comment that task criticality "appears to be an exceedingly useful measure of the degree of attention an activity should receive by management" (p. 209). However, the criticality index of a task is difficult to measure in a way that is both accurate and tractable. Elmaghraby [97] provides a comprehensive review of the literature of criticality in project networks and identifies four analytical approaches. First, Martin [205] assumes that the cumulative distribution functions of the tasks are polynomial functions of time. Their proposed approach relies on path enumeration, which makes it impractical for large networks. Second, Dodin and Elmaghraby [92] describe an algorithm that works by labeling nodes and using one-step approximated convolutions to estimate criticality indices. This algorithm discretizes continuous probability density functions and assumes that all paths are independent; i.e., they have no common tasks. Unfortunately, this assumption induces errors that grow with network size (Yao and Chu [330]). Third, Kulkarni and Adlakha [181] analyze the probability that a given path is critical for PERT networks with exponentially distributed task durations. Fourth, Bowman and Muckstadt [43] extend these results to estimate task criticality.

Chu et al. [71] define the critical path as a stochastically dominant one and one containing tasks for which the completion time of the project is more sensitive. They describe an algorithm for finding the critical path, as thus defined. The algorithm works by labeling the nodes in the project network. It discretizes the probability density function using Chebychev sampling points (Agrawal and Elmaghraby [9]) and applies a heuristic approach to compensate for paths with shared tasks. Their work has relevance to the estimation of task criticality.

Williams [322] provides examples where the criticality index fails to provide relevant information that is helpful to management and notes that the level of criticality depends on resource allocation decisions that are usually subsumed in criticality analysis. As an alternative, he therefore proposes a *cruciality* index that is based on the correlation between task and project times. Cho and Yum [68] apply Taguchi's tolerance design technique to estimate the effect of task duration uncertainty on project completion time. Vanhoucke [307] uses simulation to compare the usefulness of four task-based measures of project sensitivity. He finds that the schedule sensitivity index and some variations of the cruciality index provide the best results.

4.7.2. Future Research. The estimation of three metrics that are of use to project managers is discussed in this section. Those metrics are the distribution of project completion times and the criticality and cruciality indices of various tasks. There are several related research issues.

[RQ7.1] Regarding the estimation of project makespan and the probability distribution of project completion times, the results reported by Ludwig et al. [198] apparently provide accurate estimates, but not all companies can implement such a complex approach. A more tractable alternative, in the form of a simple yet statistically robust procedure for calculating PERT adjustment factors for project makespan, would be valuable.

[RQ7.2] Even more challenging, but potentially even more valuable, would be developing a methodology to find robust estimates of the probability of completing the project by any given time.

[RQ7.3] Similar comments apply to the estimation of criticality for the tasks. The methods described above are more complex than most companies will use; hence reliable heuristic approaches are needed.

[RQ7.4] The practical usefulness of the task cruciality and persistency concepts, relative to that of task criticality, needs to be explored in depth.

[RQ7.5] For companies that run many projects with similar network structures, it should be possible to customize and improve the general procedures discussed here.

4.8. Earned Value Management

4.8.1. Background. EVM is an accounting, monitoring, control, and forecasting system for projects. It was developed by the U.S. Department of Defense in 1962.[7] It is based on metrics that monitor the time and cost incurred by the project, relative to the schedule and budget. A key concept is the budgeted cost of work performed, also known as the earned value. The central idea of EVM is that time and cost performance should be evaluated relative to the actual progress of the project. EVM is used to compute performance metrics for the current state of the project and also to make forecasts about performance metrics at project completion. This information can be used to make resource reallocation decisions, as needed, and to communicate more effectively with project owners. Fleming and Koppelman [108] and Christensen [69] provide background on EVM. Willems and Vanhoucke [321] provide an extensive review of the EVM literature and classify it using six different criteria: assumptions of the research problem, type of contribution, type of methodology, degree of uncertainty allowed, method of validation, and type of application. Kwak and Anbari [183] note that EVM is mandated for many U.S. government projects and programs. On the basis of a study at NASA, they conclude that it provides substantial value. In 1991, performance problems identified using EVM resulted in cancellation of the Navy's *A-12 Avenger II* program.

Despite its rational justification and quite broad influence in the public sector, EVM has not been widely used in private industry. This may be partly due to its complexity and apparent cost relative to value delivered (Hazir [140]). More objectively, though, it is also due to several weaknesses or limitations. EVM does not provide a way to determine whether deviations from the project plan are within the range of normal variation or whether they indicate that the project is out of control. Acebes et al. [5, pp. 423–424] comment, "…a negative variance might be a warning sign of a problematic situation, showing that project is behind schedule or exceeding the planned budget" (pp. 423–424). This distinction is important, since it identifies whether corrective action is needed, and it also affects the assumptions on which forecasts of end-of-project time and cost will be based. Attempts to resolve this deficiency are proposed by Pajares and López-Paredes [226] and Acebes et al. [5].

Another major weakness is that EVM does not distinguish between critical and noncritical activities, although time variance is clearly a more serious issue for the former than for the latter. Furthermore, EVM assumes that tasks are independent. In practice, however, they are not; hence variance in one task may affect the performance of another. Behavioral problems also arise with the use of EVM. For example, to make cost variance positive, managers may decrease the actual cost of work performed (Kim and Ballard [169]). EVM also lacks a way to measure quality, as a result of which a project may be delivered on time and on cost but without meeting client expectations. A further problem is that EVM imposes substantial information requirements on projects. An example of such requirements is precise measurement of project progress against a very detailed work breakdown structure (Lukas [199]). Finally, Cooper [74] argues that the accuracy of EVM metrics in highly complex projects is compromised by the need for several cycles of rework.

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[7] *Wikipedia*, s.v. "Earned value management," last modified July 26, 2016, http://en.wikipedia.org/wiki/Earned_value_management.

There are some extensions of EVM that avoid the assumption of deterministic task durations for the remainder of the project required by EVM. This work includes two different branches. Naeni et al. [214] present a variation of earned value metrics based on fuzzy theory. Acebes et al. [5] integrate project risk analysis based on the application of Monte Carlo simulation to EVM. Whereas basic EVM methodology provides only point estimates, they are able to provide statistically based estimates of deviations from planned value. This enhancement provides confidence to managers who need to make resource allocation decisions based on EVM.

Lipke [193] identifies problems with the use of EVM for the purposes of project planning and control. For example, toward the completion of a late project, EVM's schedule variance converges to 0 and its schedule performance index converges to 1. Hence, during that period, it is difficult for a project manager to justify a request for additional resources, even though they are needed. He therefore proposes earned value scheduling (EVS) as an alternative to EVM. To estimate the project time at completion, EVS uses the planned duration, the earned schedule which is the time at which the current project progress should have been achieved, and an assumed performance factor. Regarding the estimation of project time at completion, Vanhoucke and Vandevoorde [309] find, as a result of an extensive simulation study, that there is a clear computational advantage for the use of EVS over EVM. Extensions of EVS that incorporate rework and activity sensitivity are developed by Batselier and Vanhoucke [29], and the resulting forecasts are compared with several benchmark approaches using data from 51 real projects. Lipke et al. [194] apply statistical methods to both EVM and EVS performance metrics in order to obtain more accurate forecasts. Caron et al. [58] develop an enhancement of EVM using data and expert opinion within a Bayesian format.

It is also important to estimate project cost at completion in order for the project manager to communicate cost overrun information with the project owner, when necessary. Narbaev and De Marco [216] identify problems in using EVM for this purpose, including a reliance on unrepresentative data from early in the project and naïvely simple extrapolation of past performance into future performance. To correct for these problems, they develop a nonlinear regression model that tracks the relationship between time and cost using parameters that can be estimated from project data and incorporates the EVS estimate of project time at completion. The predictions of estimated project cost at completion obtained from their procedure are more accurate, with mean errors of 4.2% early in the project and 3.2% late in the project, than those found by several benchmark procedures.

4.8.2. Future Research. The restrictive assumptions, methodological weaknesses, and limited application of EVM suggest several important research issues.

[**RQ8.1**] Kwak and Anbari [183] propose that EVM can be used to encourage innovation and to enable more precise estimates of changing project resources and scope, and the effectiveness of these ideas needs to be studied.

[**RQ8.2**] Willems and Vanhoucke [321] recommend four research directions as most important: greater incorporation of stochasticity, more complete validation of methodology using large data sets or simulation, increased consideration of quality and sustainability issues, and the development of improved corrective action procedures. All these directions should be explored.

[**RQ8.3**] There is a need for a survey study to identify from the viewpoint of decision makers the reasons why they do not use EVM.

[**RQ8.4**] There is a need to identify additional features that should be incorporated in an improved monitoring system without making it so complicated that it would not be widely used.

[**RQ8.5**] EVM needs to be adapted to monitor progress and make reliable forecasts in a critical chain project management system.

[RQ8.6] Agile project management methodology (Agilemanifesto.org [8]) is not well served by EVM, because the percentage of work completed is difficult to estimate in a flexible planning system. Hence, there is the potential to develop a new procedure to monitor progress more precisely and thus to generate more reliable forecasts for agile projects.

[RQ8.7] The literature on estimating project cost at completion from the data of a partially executed project mostly considers expected cost, which implicitly assumes risk neutrality on the part of the project manager. However, since projects can be financially large relative to the size of the organization, some measure of risk aversion (Rabin [250]) is appropriate. Hence, it would be valuable to study not only the expected project cost at completion but also its probability distribution.

4.9. Multitasking

4.9.1. Background. The concept of multitasking is a familiar one in computer systems. In that context, it is defined as follows: "In computing, multitasking is a method where multiple tasks, also known as processes, share common processing resources such as a CPU" (Appasami and Suresh Joseph [16]). An operational definition of multitasking is that more than one task can be partially executed at the same time. Sachdeva and Panwar [264] review various scheduling algorithms that are needed for multitasking. Models and algorithms for efficient computer multitasking in specific applications have been studied by various researchers. These include Noguera and Badia [220] and Steiger et al. [286] for reconfigurable architectures, and Wang et al. [315] for energy-sensitive dynamic slack allocation.

However, when tasks are processed by humans rather than computer systems, different multitasking issues arise. This situation arises in a wide variety of applications—for example, administration, manufacturing, and process and project management. In project management, multitasking means that resources are shared between multiple tasks or even across multiple projects, and as a result, work on a task is interrupted before completion.

Discussions of the motivations for human multitasking can be found in the literature of behavioral psychology, operations management, cognitive engineering, and project management. Jez [161] provides an integrative review of the multitasking literature.

Hall et al. [131] identify five factors that motivate human multitasking:

1. A need to feel or appear productive (Huff [154])
2. A need to demonstrate progress or equitable treatment for various tasks (Elder [96])
3. Anxiety about the processing of waiting tasks (Morgenstern [210])
4. A need to alleviate boredom or increase variety in work (Cantor [55])
5. Interruption by routine scheduled activities (Jett and George [160])

In project management, it is frequently the case that many tasks are being performed concurrently by different resources. As a result, there are situations where multitasking is needed in project management. An example occurs in critical chain project management (Goldratt [118]), where the impending depletion of a feeding buffer threatens the critical chain. Such an arrangement is often essential for efficient completion of a project and can be viewed as "good multitasking." However, when the same resource alternates between tasks, or shares its capacity between multiple tasks, substantial inefficiencies can arise. In part, they arise from the process of switching between tasks, which results in lost time and also quality problems.

Although many people feel productive when multitasking, in fact, the costs of multitasking are considerable. Based on the results of a case study of 45 organizations (Realization [255]), multitasking reduction programs can achieve an average improvement of 60% in productivity. A global extrapolation of these results provides an estimate of $450 billion annual cost of multitasking. An even more impressive estimate of $1 trillion is provided by Suddath [291]. Rand [252] describes multitasking as an important aspect of project management that needs to be controlled. Leach [187] discusses the widespread presence of multitasking in project management and the resulting problems that arise.

Yaghootkar and Gil [327] study the problem of "schedule-driven" multitasking in project management. They comment that a "fundamental insight that emerges from studies of multiproduct organizations is that specialized resources switch frequently between projects in these settings, and this is a root cause of schedule pressure" (pp. 127–128). This especially happens when senior management transfers resources from other projects, to assist a high-value but delayed project. This procedure is often ineffective (Brooks [47]). Additionally, productivity is often reduced because learning opportunities are lost as a result of switching work (Abdel-Hamid [1]). From an empirical study at a truck manufacturer, Yaghootkar and Gil [327] identify a cascading effect whereby more and more projects come under pressure as resources are shifted between them. They therefore argue for better incentives that do not reward short-term fixes that result in long-term detriment to the organization's performance. Czerwinski et al. [77] report the results of a diary study of multitasking information workers. Their focus is on the difficulty of returning to a task after being removed from it and working on a different task. Their results show that the main factors that influence the difficulty of returning are task complexity, task duration, length of absence, number of interruptions, and task type.

Some modern project management methods are designed in part to eliminate or reduce this "bad multitasking." For example, critical chain project management (Goldratt [118]) does so by reducing the number of projects that are in process at the same time, either by delaying their start or by putting them temporarily on hold (Leach [187]). On the other hand, agile project management (Agilemanifesto.org [8]) does so by focusing the short-term objectives of the project on a small set of tasks defined by a sprint backlog. Since the number of tasks is smaller, there is naturally less multitasking.

The scheduling literature contains recent results on multitasking environments. Hall et al. [131] develop optimal algorithms for some fundamental and practical single-machine scheduling problems with multitasking. They show that other problems are computationally intractable, even though in some cases the corresponding problem in classical scheduling is efficiently solvable. They also study the cost increase and value gained as a result of multitasking, which informs companies about how worthwhile it would be to invest in measures to reduce multitasking. Hall et al. [132] develop scheduling models and algorithms that allow breaks, either to alleviate boredom or to perform routine scheduled tasks, thereby mitigating the loss of productivity in such situations. One model applies "alternate-period processing" and aims either to allow workers to take breaks or to increase workers' job variety. Another model applies "shared processing" and aims to allow workers to share a fixed portion of their processing capacities between their primary tasks and routine activities. Both models are solved using fast optimal algorithms, where possible.

4.9.2. Future Research. The recent developments in algorithms for scheduling with multitasking discussed above suggest the possibility of using them for more efficient multitasking in project management. This can be implemented, for example, through the resource leveling step in Microsoft Project. There are several related research issues.

[RQ9.1] The recent results for scheduling with multitasking discussed above need to be extended into the project management environment by the consideration of precedence constraints.

[RQ9.2] It is important to incorporate switching time, i.e., time lost when changing between tasks when multitasking, into resource-leveling rules.

[RQ9.3] Another challenge is how to incorporate the need for work on tasks to be either partially or completely repeated when it is interrupted.

[RQ9.4] The effects of multitasking on quality and creativity have not been studied for business processes; indications are that such issues may be significant (Elder [96], Jez [161]).

[RQ9.5] The recent research discussed above motivates the development and evaluation of practical measures to reduce or increase multitasking by the waiting jobs. Such measures include ensuring physical separation of the waiting jobs, imposing administrative controls on those jobs, and designing appropriate incentives that encourage focus on the scheduled job (Babauta [26]).

[RQ9.6] There is a need to evaluate the costs incurred by multitasking, relative to other priority approaches, in managing multiple projects.

4.10. Optimization of Work Breakdown Structure

4.10.1. Background. A work breakdown structure (WBS) defines the relationship between the project as a whole and its individual tasks. This planning tool was developed jointly by the U.S. Department of Defense, NASA, and the aerospace industry (Department of Defense/National Aeronautics and Space Administration [85]), and it is viewed as a fundamental preliminary step in project planning (Golany and Shtub [117], Kerzner [168]). A WBS is an exhaustive and mutually exclusive decomposition of a project into successively smaller components using a hierarchical tree structure. Its contributions to project planning include the following: (i) it provides a well-defined overall project organization; (ii) it unambiguously assigns responsibilities for work; (iii) it identifies project milestones and points for benchmarking the progress of the project; (iv) it supports estimation of cost, risk, and time; and (v) it helps to explain the project scope to stakeholders. Demeulemeester and Herroelen [83] describe the process by which a company develops a WBS. Globerson [114] summarizes the importance of a WBS: "The correct use of a WBS contributes significantly to the probability of successful project completion" (p. 166). While this statement is intuitively reasonable, it would be valuable to test it empirically.

The most important output of a WBS is a "work package" that is assigned to a specific organizational unit. Work packages are composed of one or more elemental, or "atomic," tasks. Various informal principles underlie the sizing of work packages—for example, that they should be large enough to be measurable but small enough to be manageable. Globerson [114] illustrates how five distinctly different WBS structures can reasonably be generated for a new restaurant development project, each based on a different sequence of breakdown criteria, level by level, within the WBS. This example identifies the choices in work package design that may fundamentally influence project performance, yet these choices have not been studied from the perspective of optimizing project time and cost performance.

Two issues arise from this variety of choices. First, dependent on the WBS chosen, the work packages that are used to perform the detailed planning and scheduling of the project may be different. Differences in work package definition also produce differences in precedence relations between them, which in turn affects opportunities for concurrent processing (Hoedemaker et al. [151]). For example, further decomposition of work packages creates opportunities for additional concurrent processing of tasks; however, this is not always beneficial since the planning complexity of the project is increased. Second, even if the work packages resulting from different WBSs are the same, the level of compatibility between the WBS hierarchy and the organizational structure may vary considerably. Both these issues may affect the time and cost performance of the project.

The importance of work package sizing is illustrated by the following comments from practicing project managers:

— "Whichever maximum increment of time you choose to breakout your tasks will directly impact your ability to track progress and give accurate project status reports to sr mgmt."[8]

— "There are trade-offs. Too high a level, the administrative burden to manage it is less in terms of cost. However, you lose insight into what is going on in the work and to understand

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[8] R. Kastner to Project Management Central, July 17, 2001, http://www.projectmanagement.com/discussion-topic/2031/The-standard-for-work-packages-/?sort=desc&pageNum=1.

where variances are accruing and why. This lack of insight increases your risk of successful ability to mitigate those variances”[9]

Some rules of thumb for work package sizing are already in use in project management practice. In 1972, the U.S. Department of Defense recommended a work package size of six months of development time or $100,000 of cost, as reported by Brown [48]. However, Devi and Reddy [86] suggest that a work package should comprise between 8 and 80 hours of work. Some project managers recommend smaller work package size designs such as requiring work packages to be at least 4 hours and at most 40 hours in duration (Kennemer [167]).

The academic literature also considers the issue of work package sizing. Raz and Globerson [253] identify the following factors as important for project managers to consider in determining the sizes of their work packages.

— *Workload*: Decomposing the project into more but smaller work packages increases the workload complexity of the project manager and the project team.

— *Cost and schedule estimation*: Estimates of cost and schedule at completion of the work package are more accurate for work packages with smaller content.

— *Monitoring and control*: It is easier to monitor and control the progress of work packages with smaller content.

— *Cash flow*: Smaller work packages lead to earlier completion of tasks and improve the project’s cash flow.

— *Network construction and concurrent processing*: Aggregation of atomic tasks into work packages may reduce opportunities for concurrent processing.

— *Responsibility assignment*: It is necessary for a single person or organizational unit to take responsibility for the entire work package.

— *Internal cohesion*: Some groups of atomic tasks require close coordination among them.

— *Risk management*: A high-risk activity should be assigned to a separate work package to avoid contagion of other tasks.

There are several research studies about WBS design. Deckro et al. [81] study a project scheduling problem with a time–cost trade-off, where the project tasks are partitioned into work packages, each with a given due date and budget. The objective of their problem is to minimize the total project cost, subject to the due date, budget, and precedence constraints. They solve this problem using mathematical programming. Luby et al. [197] discuss the application of a customized component-based WBS to projects in naval shipyards. This design enables continuous accountability for each component while allowing flexibility for work plans. Jung and Woo [163] propose a WBS that is flexible, in that it allows different management approaches to be applied to different work packages, in order to reduce the amount of information required in project planning. Danilovic [78] notes the benefits of having suppliers involved in new product development projects but demonstrates how functionally designed WBS and work package structures create barriers that prevent this. The proposed solution involves a more collaborative WBS and work package system, based on a dependency structure matrix. Other researchers study WBS design from the perspective of systems development. Golpayegani and Emamizadeh [121] apply neural networks to plan WBSs and consider a project control WBS, a functional WBS, and a relational WBS. Bai et al. [27] similarly use domain tree structures, domain WBSs, and relational WBSs. Li and Ren [191] focus on the relationships between objects in cloud manufacturing, the availability of cloud services resources, and service access issues.

Hall and Li [189] study how design decisions at the planning stage of a project affect its performance. This work is apparently the first to solve the work package size trade-off for optimal project performance. The objective of minimizing total cost, subject to a project makespan deadline, is considered. For subsets of tasks in series, an efficient algorithm that

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[9] D. Espina to Project Management Stack Exchange, May 3, 2011, http:pm.stackexchange.com/questions/2003/what-is-the-right-approach-to-work-package-size.

finds optimal work package sizes is provided. For subsets of tasks with general acyclic network structure, a heuristic method and lower bounds are described for the highly intractable problem. A computational study shows that these solution methods routinely deliver near-optimal solutions and substantial improvement over widely used benchmark approaches.

4.10.2. Future Research. Several issues remain open for future research on the topic of WBS design.

[RQ10.1] The literature is deficient as to understanding the extent of differences in performance that result from the choice of WBS. A thorough empirical study is needed to resolve this deficiency. For example, it would be valuable to know whether some WBS designs provide particularly effective schedule performance, whereas other designs are effective at controlling cost.

[RQ10.2] It would be valuable to conduct an empirical study to estimate the strength of influence of the various factors discussed above on project performance.

[RQ10.3] For particular project management applications, the factors that affect work package sizing may vary from the generic ones discussed in Hall and Li [189]. It would be highly useful to identify such factors for those applications.

[RQ10.4] Some factors such as the cost of inaccurate estimation may benefit from being modeled more precisely using stochastic functions, and some factors such as the cash flow penalty may be modeled more precisely using task-dependent parameters.

[RQ10.5] There is apparently no work that focuses on the sequence of criteria that are used to break the project down, as distinct from work package sizing. It may be possible to develop a model that simultaneously optimizes the sequence of criteria used and the work package sizes. As Globerson [114] notes, the sequence of criteria used interacts strongly with issues of organizational and managerial culture; therefore, a model of this type needs to include behavioral issues.

4.11. Learning Within a Project

4.11.1. Background. Modern applications of project management often define projects with characteristics that make them especially challenging. In many projects, especially those with longer durations, substantial learning takes place during project execution. This learning can be used to improve the performance of the remaining tasks. Thus, an important issue is to investigate the potential for learning within a project, or *intraproject learning*, to optimize project performance. Learning between projects, or *interproject learning*, is studied by Pich et al. [234] and Schindler and Eppler [268], and it is not discussed further here. Turner et al. [303] lament that “Valuable learning experiences take place at the beginning of the project, but are not captured until the postproject review at the end” (p. 17). Williams [323] discusses best practices for lessons learned within project management and also recommends the documentation of lessons learned within unfinished projects.

During execution of a project, learning occurs in at least two ways. First, the tasks themselves become better understood. An example occurs in a new product development project, where there may be problems working with an unfamiliar material on tasks early in the project. Resolution of these problems then suggests potential solutions when using the same material in later tasks. Another example occurs frequently during IT implementations, when it becomes clear during the project that more user training than anticipated is needed. Second, the efficiency and reliability of the resources that are available for the project become more precisely known. An example occurs when a subcontractor is unreliable in supporting a task that is early in the project. This suggests allowing more time for a later task supported by the same subcontractor, or even finding an alternative subcontractor. Similar issues arise with project teams that have underperformed on previous tasks but will nonetheless be needed for later tasks.

The process of intraproject learning can occur in two different ways. First, it can occur *autonomously* as the project executes. That is, as a result of experiences with tasks early in the project, the efficiency of later tasks becomes greater without the need for any investment of time or other resources. We recognize the usefulness of autonomous learning but propose research on the additional improvement in project efficiency that can be achieved through investment in *deliberate* learning. The project management literature supports this focus. Ayas [23] writes, “Learning within a project does not happen naturally; it is a complex process that needs to be managed. It requires commitment and continuous investment of resources” (p. 131). Ayas and Zeniuk [25] comment further, “Learning is not a natural outcome of projects and a project-based organization is not necessarily conducive to learning.” The business literature also supports the need for deliberate learning, as discussed by Darter [79]: “Being able to document lessons learned after a project is complete (or even in the middle of it) is one of the biggest responsibilities a project manager has on a project.” Best practices for documenting lessons learned are presented by Sabyasachi [263].

There are various studies of learning strategies and effects in the related literature. The classic work of March [203] studies the tension between devoting learning resources to exploring new directions and devoting those resources to exploiting old ones. Shipton et al. [279] identify factors that predispose manufacturing organizations to adopt effective learning processes. Within the scheduling literature, the typical model uses learning by doing (Biskup [38], F. Kupers [182]), where learning effects are autonomously realized as a result of repetitive processing of a large volume of similar products. However, such volume effects are rarely present within projects as a result of their uniqueness (Kerzner [168], Wysocki [326]). Moreover, Hatch and Mowery [138] observe from their study of manufacturing companies that, “in contrast to most previous studies of learning by doing, the learning curve is shown here to be the product of deliberate activities . . .” (p. 1461). Within a project management environment, Ayas [24] proposes the use of a generic work breakdown structure as a way to enhance organizational learning. Sense [275] recommends the use of supportive learning environments within projects as a way to enhance learning. Kotnour [180] describes organizational learning practices to ensure project quality and provides a framework that defines typical learning processes. This framework is supported by the results of a survey about the relationship between learning practices and project performance.

The literature includes several works that treat the amount of learning as a decision variable. Li and Rajagopalan [190] describe a model that includes the effects of autonomous and induced learning on both productivity and quality. Carrillo and Gaimon [59] discuss how plant performance is impacted by investments in workforce training and process change. However, these works consider continuous manufacturing environments, where knowledge gains are not attributable to specific discretely defined tasks, as they are in projects.

In developing models and solutions for optimal intraproject learning, the main variable to be considered is how much investment should be made in learning on completion of each task. This amount necessarily depends on the knowledge contribution of the completed task to future tasks within the project; the greater the contribution, the more investment is worthwhile. The durations of future tasks depend on previous learning and task characteristics. Diminishing returns to time and resources invested in learning need to be considered. Cao et al. [56] develop and solve a model to identify the optimal amount of time to invest in learning during a project. This research direction should provide project managers with information about the right amount of learning to use at various stages of a project, to balance the trade-off between resources invested in learning and the value of the lessons learned. Because the similarity of issues that arise between tasks is greater within a project than between projects, the insights gained from the optimization of intraproject learning are different from those found within the literature of learning between projects.

4.11.2. Future Research. Learning within projects has the potential to improve performance considerably for some projects. Realizing that potential fully requires addressing the following issues.

[RQ11.1] An optimal intraproject learning model requires two special types of data: rates at which investment in learning generates knowledge from each task and rates at which previously acquired knowledge can be applied to reduce the durations of future tasks. A procedure can be developed to estimate these data empirically for a given project.

[RQ11.2] Besides the optimization procedure proposed by Cao et al. [56], there is a need for a simple heuristic procedure that can be implemented quickly by project managers. For this purpose, it will be useful to estimate the managerial value of knowledge for different tasks.

[RQ11.3] There is a need to incorporate the cost, and the time value of money, into an optimization model of intraproject learning.

[RQ11.4] Project management objectives other than the minimization of makespan need to be considered; for example, project revenue based on completion time can be modeled.

[RQ11.5] Specific project management applications—for example, some change management projects—may present different learning processes that can be modeled to optimize intraproject learning.

4.12. Managing a Secret Project

4.12.1. Background. In highly competitive industries, including consumer electronics, computer games, and pharmaceuticals, obtaining information about a product in development can provide a substantial advantage to a competitor. For example, the competitor can use this information to decide whether to accelerate its own products in development, modify them, or abandon them (Lavelle [186]). For this reason, economic espionage is a common problem in competitive industries. Samli and Jacobs [265] comment, "…the steadily increasing value of trade secrets and the spread of technology throughout the globe combined, created a significant increase in both the opportunities and motives to perform economic espionage" (p. 96). Nonetheless, estimates of trade secret theft range from 1% to 3% of GDP in advanced economies (PriceWaterhouseCoopers [243]). Industrial espionage costs U.S. businesses over $300 billion annually (Samli and Jacobs [265]). As a result, a project company needs to minimize or delay its information loss in order to reduce potentially damaging reactions by competitors (Puchko [248], Yarow [331]). This objective leads to the use of secrecy and deception. Pinker et al. [235] give an example of the UK supermarket chain Tesco, which explored the Los Angeles market while disguising their new store as a movie set. Sanger [267] suggests that Iran has used a misinformation strategy to disguise its ongoing nuclear weapons program.

A secret project is any project with a value that is potentially changed by observation and reaction by a competitor. In a secret project management environment, the project company uses various approaches, including scheduling, crashing, and deception, to increase the value of its project. Examples of specific business practices where additional decoy work and cost are introduced into projects, to deceive competitors and thereby protect the competitive position of the project company, include the following:

(1) Tidewater conducted irrelevant land surveys in the 1870s to deceive the industry leader Standard Oil about the planned route of its competitive pipeline (Hendricks and McAfee [142]).

(2) Palm introduced its handheld device in 1996, after an extensive publicity campaign that presented it as a complement, rather than as a substitute, to a personal computer, thereby delaying a competitive reaction by Microsoft (Yoffie and Kwak [333]).

(3) In the pharmaceutical industry, Genentech researched and published several alternative ways of accomplishing the same task, without revealing which one was most efficient (Langinier [185]).

(4) In developing several new products, Capital One advertised more broadly and expensively than necessary to obscure their real target customers to industry leaders such as Citibank (Yoffie and Kwak [333]).

(5) Hendricks and McAfee [142] describe how Microsoft used a file system known as WinFS, which was apparently in development but was never introduced, as a decoy to deter competitors.

(6) Dormehl [94] describes how Apple uses patents to mislead competitors for products that Apple has apparently already decided are not worth developing.

In computer network defense, a cyber-deception operation is a set of actions to mislead attackers and thus cause them to take action or inaction that benefits the defense (Stoll [289], Yuill [334]). The purpose of a deception operation is to deceive the attacker into a predictable course of action or inaction that can be exploited by showing the attacker what is false and hiding what is real (Bell and Whaley [32]). Whaley [318] illustrates how the use of deception affects standard economic insights. Ryu et al. [261] model a system designer's defensive actions against intruders in a way that maximizes the difference between the intruders' cost and the system designer's cost of system protection. The results of the proposed model provide the system designer with insights about the right level of protection.

Averbakh and Lebedev [22] study the problem of project scheduling by a company that competes with another company over the same project. Each company's profit depends on its project completion time, relative to that of its competitor. The objective is to maximize the guaranteed, i.e., worst-case, profit. They provide a detailed algorithm, computational complexity analysis, and heuristic worst-case analysis of several variations of the problem. Averbakh [21] discusses the efficient identification of Nash equilibrium solutions, or in some cases shows that none exist, for this problem. Brown et al. [50] study a problem involving the development of nuclear weapons. An interdictor takes actions that maximally delay a weapons development project by a proliferator, and the proliferator adjusts its plans to minimize that delay. They solve a case study using project management software and provide insights about diplomatic, economic, and military options. Lunday and Sherali [200] discuss a dynamic network interdiction model where an interdictor deploys resources on arcs and an evader traverses the network between a given source and sink. They provide an optimization model and a heuristic, and they discuss stability and convergence issues.

Pinker et al. [235] discuss the management of a secret project. The problem studied involves project scheduling in a competitive environment with an adversary, such as a competitor company. As the tasks of the project are completed, the adversary obtains a clearer understanding of the project, until at some point the project is fully "exposed." The objective is to minimize the difference between the project completion time and the time of exposure. The project manager uses a combination of task scheduling and crashing to achieve this. They establish intractability of a general form of their problem and provide efficient solution procedures for special cases. Some results about the solvability of related problems appear in Pinker et al. [236].

Wen and Hall [317] examine the secret project management problem under competition, and they model this problem as a two-stage Stackelberg game. The project company is the first mover of the game. The project company makes decisions about scheduling, crashing, and deception to minimize the information loss to the competitor, subject to a given project makespan and a budget for crashing and decoy work. The project company protects its project by doing additional decoy work. After observing each task's work content, the competitor makes a decision about the cost-effective level of validation of the information. The project company's decisions are based on (a) information that is public and (b) a prediction of the competitor's decisions. A surprising insight is that it benefits the project company to announce that it uses decoy data.

4.12.2. Future Research. The secret project environment suggests several interesting research questions.

[RQ12.1] Various possible objectives can be considered for this problem, for example, based on not only the project makespan but also the completion times of several milestones within the project.

[RQ12.2] It would be valuable to consider stochastic task times with known probability distributions; crashing can still be used to modify those distributions favorably.

[RQ12.3] There can be multiple levels of understanding of the project by the adversary, which can systematically reduce the choices and/or outcomes of the project manager.

[RQ12.4] The information available to the different parties can be modeled in various ways—for example, symmetrically or asymmetrically.

[RQ12.5] The mechanism by which the adversary learns about the project can be modeled in a variety of practically relevant ways.

[RQ12.6] Existing models of secret projects with a single competitor can be extended to include multiple potential competitors of the project firm.

[RQ12.7] Models of strategic behavior can be used to increase the range of options available to the adversary; for example, the adversary could attempt to mislead the project company as to its intentions.

4.13. Buffer Sizing in Critical Chains

4.13.1. Background. The influential work of Goldratt [118] has popularized the alternative project planning approach of CCPM. The critical chain is defined as the set of tasks, considering both precedence and resource availability, that determines the overall project duration (Patrick [228]). The critical chain is protected by three types of buffers. A project buffer at the end of the critical chain protects the project delivery date. Resource buffers serve as warning devices to ensure that resources are ready when needed. Feeding buffers prevent delays on noncritical chains from affecting the performance of the critical chain. The size of these buffers is important. Buffers that are too large add costs and make bids less competitive, whereas buffers that are too small result in either financial penalties for late project delivery or expensive crashing or outsourcing measures to avoid those penalties (Tenera [296]). Problematically, however, the CCPM literature provides no definitive guidance about how buffer sizes should be determined (Ashtiani et al. [18]).

Vanhoucke [308] summarizes the four most commonly used buffer-sizing approaches and provides evaluative comments. Each of these methods first estimates, for each task, an aggressive or optimistic duration and a safe or conservative duration. The standard deviation of each task is then estimated as half the difference between the safe and aggressive estimates. However, a plausible alternative here is to use the three-point estimation procedure from PERT and take the standard deviation as one-sixth of the range. In either case, on the basis of an assumption of independence of the task durations on a chain, the standard deviation of the length of the chain that feeds the buffer is calculated as the square root of the sum of the task duration variances on the chain. These four established buffer-sizing methods are as follows:

(1) *Cut and paste* (Goldratt [118]): The buffer size is half the sum of the aggressive task durations on the feeding chain.

(2) *Root square error* (Newbold [219]): The buffer size is the square root of the sum of squares of the differences between the safe and aggressive task duration estimates over the feeding chain.

(3) *Adaptive density* (Tukel et al. [301]): The buffer size is the standard deviation of the feeding chain, multiplied by $(1 + d)$, where d estimates the density as the number of precedence relations in the chain divided by the number of tasks.

(4) *Adaptive resource tightness* (Tukel et al. [301]): The buffer size is the standard deviation of the feeding chain, multiplied by K, where K denotes the maximum resource utilization rate across all resources.

We provide some comments about these four methods. The cut-and-paste method, while easy to implement, suffers from oversimplification, and therefore it does not perform robustly across various projects. Furthermore, it causes project buffers to be unnecessarily large, which wastes resources, as validated by computational studies (Herroelen and Leus [147]). A more formal critique is provided by Ashtiani et al. [18], who use a statistical analysis to show that the cut-and-paste method results in substantial waste. The root square error method can be justified from the central limit theorem (Black [39]) and the assumption of independent task durations within the chain. However, this assumption is frequently not justifiable in practice, particularly where the same resources are used for different tasks. Consequently, buffer size calculations from the root square error method are often too small (Radovililsky [251]). The rationale underlying the adaptive density method is that the presence of more precedence relations for the same number of tasks makes the project more vulnerable to delays, which necessitates a larger buffer. Similarly, the adaptive resource tightness method can be justified from the perspective that a higher average resource usage rate is more likely to result in delays to the project.

Besides these established buffer-sizing methods, there are some evolving research directions. One of them is consideration of the importance of information flow as a characteristic of a project. Yang et al. [329] discuss the interaction of information flow and propose to reduce it with the use of a sensitivity design structure matrix. Steyn [288] consider an information exchange model that allows representation of complex task relationships. Second, other project characteristics that are considered include the flexibility coefficient of the project (Steyn [287]) and project managers' attitudes to risk (Chu [70]). A third approach is the use of fuzzy theory. Shi et al. [277]) use a combination of fuzzy theory and resource substitutability to achieve computational results that are more accurate than those obtained from the standard methods.

Zhang et al. [335] apply a combination of several of the above approaches in a comparatively complex approach. Their formula for buffer size incorporates resource working efficiency, which includes the components of the resource utilization, the proportional cost of each resource in total resource costs, the activity duration considering overlapping relationships, the task cost as a proportion of the total cost, and the flexibility of task start times. Using 500 simulation runs, they compare their approach with the four basic standard methods on a project with 12 tasks, and they obtain small delay probabilities and a reduction in cost. This combination method appears to have good potential.

4.13.2. Future Research. Because of the widespread use of CCPM, further refinement of buffer-sizing methods would be highly valuable, in several directions.

[RQ13.1] There is still a need to compare the various existing methods using a comprehensive computational study. In particular, combination methods such as those proposed by Zhang et al. [335] need to be tested against other methods for large projects.

[RQ13.2] In most projects and perhaps particularly in IT, the level of resources that is available to the project varies over time, and there is apparently no work that takes this into account.

[RQ13.3] It would be valuable to develop buffer-sizing rules for particular project management application areas where uncertainty in task times does not fit a generic statistical pattern. An example is projects for an end user within the organization, such as change management projects.

[RQ13.4] More research is needed on the impact of human behavior and psychological factors. In particular, the interaction between setting buffer size and the influence of Parkinson's law (Parkinson [227]) may turn out to be significant, and it has apparently not been studied.

[RQ13.5] The development of dynamic rules would be useful for situations where the project risk level changes during execution, or where real-time information affects project characteristics. Examples of the latter situation occur when the project deadline changes as a result of activity by a competitor or when the project owner changes the scope.

4.14. Traditional vs. Agile vs. Hybrid Methodology

4.14.1. Background. Many traditional applications of project management methodology are largely deterministic; i.e., the final configuration of the end of project deliverables is specified before the start of project execution. Examples of deterministic applications include construction and engineering, where detailed blueprints are developed during project planning. By contrast, many modern applications are characterized by uncertainty about the final project configuration, and new information that resolves that uncertainty is revealed as the project execution proceeds. Depending on the application, this information is revealed as a result of testing, consumer focus groups, clinical trials, regulatory decisions, or technological and business developments. Examples of such nondeterministic applications include research and development and the development of software, pharmaceuticals, and new products and services. A widely used response to the different characteristics of modern projects is the development of agile project management methodology (Agilemanifesto.org [8]). The principles of agile project management include reduced planning and documentation, as well as the submission of prototype deliverables in small increments, followed by rapid user feedback and rework.

The choice of appropriate project management methodology is highly dependent on project characteristics. In many projects, the final project configuration is mostly deterministic and the planning requirements are not excessive, often because of the earlier performance of similar projects. An example of this type of commodity project is an annual software upgrade. Such projects should be managed using traditional methodology (Nerur et al. [218]). In research and development projects, however, the flexibility provided by agile methodology is an essential asset (Boehm [40]). There are also many intermediate projects where the choice of methodology is less obvious. An example is many new product and service development projects (Smith [283]). An important question, then, is under what conditions a project should be organized using a traditional or "waterfall" process or using agile methodology.

This issue is discussed by various authors, most frequently in the context of software development projects. Paykina and Zhou [229] compare the performance of traditional plan-driven and agile methodologies for software development projects. The purpose of their study is to identify the main organizational and project characteristics that are significant factors in this choice. A series of interviews and questionnaire processes with experienced employees of an IT company identify four significant characteristics: project complexity (e.g., project size, the number of parts), communication capability between the customers and the project team, competencies (e.g., knowledge, abilities, skills, motivations, attitudes) and product requirements (e.g., accuracy, urgency).

Estler et al. [102] examine 66 globally distributed software development projects run by 31 companies. The project performance criteria studied include (a) overall success, (b) economic savings, (c) the importance customers attribute to projects, (d) the motivation of the project team, and (e) the amount of real-time communication needed during project development. Their results show no significant differences in the project performance that results from the two methodologies. However, the range of applications used in this study is rather narrow, and hence the same conclusions may not apply more generally.

Thummadi et al. [299] compare software development projects with waterfall and agile process by using a Markov chain analysis. They observe that the waterfall processes concentrates work on the design stage, whereas the agile process distributes the work more evenly.

Also, the agile process introduces quality control much later, which results in numerous late-stage program bugs. Chang and Lu [63] use source code analysis and text analysis to compare the two methodologies, and they conclude that the resulting software product is very similar. A study of the software development life cycle by Leau et al. [188] emphasizes the need for sound business knowledge and strong interpersonal skills among agile developers; without these characteristics that are essential to the successful use of agile methodology, a waterfall approach may be a better option.

Kannan et al. [164] compare waterfall and agile processes for software development. They identify the advantages of a waterfall process as, for example, providing very clear and detailed planning that simplifies execution and providing clarity to users, early fault detection, strong documentation and control, and effectiveness for future planning. However, there are disadvantages. The development model is inflexible, it does not accommodate risks and emergencies well, it does not deliver a product until late in the process, and it also fails to recognize integration issues until late. They recommend the use of a waterfall process for projects with well-defined products and with more focus on scope and quality than on schedule. They identify the advantages of agile as, for example, requiring the use of fewer resources, allowing for easy and flexible management, and enabling better communication with users. On the other hand, agile is not suitable for handling complex dependencies; it requires substantial monitoring, it may not deliver precisely defined scope effectively, and it provides poor documentation.

We summarize the factors that the literature has identified as favorable toward the choice of agile methodology over waterfall methodology, and we provide a brief interpretation of each:

— *The project deliverables are not well specified.* Much of the potential benefit from agile arises from its delivery process that incrementally specifies deliverables.

— *Rapid completion of the project is a high priority.* Agile methodology emphasizes speed to completion, potentially with the loss of some cost or scope control.

— *There is availability of an experienced, cross-trained project team.* In agile project development, the management functions are shared, and informed team collaboration is essential.

— *Project team members have strong interpersonal skills.* A high level of constructive communication is required within an agile process.

— *There is availability of a fast test and response mechanism.* Agile methodology requires repeated and timely evaluation of prototypes.

— *There exists a supportive corporate culture.* A highly regulated and bureaucratic corporate culture limits the potential of agile methodology.

— *Collocation of the project team is possible.* A collocated project team is most productive and creative.

— *The project team is small.* Agile methodology was developed for teams of up to 15; the issue of scalability is discussed in Section 4.15.

— *The project can be divided into modules.* Agile works well in a modular design environment since the Scrum implementation system is highly compatible with modularity.

— *The project has few dependencies within the organization.* Relying on frequent, detailed communication with the organization reduces the speed of agile methodology.

— *Senior management demonstrates strong commitment.* Effective implementation of agile often requires cutting through "red tape," which requires senior management support.

— *Continuous, incremental implementation is possible.* The iterative development process used by agile requires incremental implementation.

— *Archiving of lessons learned from the project is not critical.* Agile methodology uses relatively limited documentation, which inhibits learning from a project to improve the execution of future projects.

It is possible to incorporate some features of both waterfall and agile processes into the same project. Hayata and Han [139] design an innovative hybrid model for IT project development. They use waterfall planning to identify user and system requirements and agile planning for design, implementation, and testing. Thus, the start and end of the process apply waterfall methodology, and the middle part applies agile methodology. The potential advantages are reduced ambiguity at the start, faster iterative development and reduced rework in the middle, and more precise and user-focused product deployment at the end. The rational unified process (RUP) (Ambler [13]) identifies six engineering disciplines that are managed along waterfall principles: business modeling, requirements, analysis and design, implementation, testing, and development. Also, three supporting disciplines are managed along agile lines: change management, project management, and team communication. Tanveer [295] describes a development model that is a hybrid between RUP and agile. This model proposes reducing these nine disciplines to seven, based on mapping to Scrum artifacts. The model is successfully implemented for a management information systems project.

4.14.2. Future Research. Apparently, no standard protocol exists for making the choice of methodology. This leads to several research issues with large financial impact.

[RQ14.1] A factor-based approach seems ideal for establishing such a protocol. It would be valuable to consider the above factors in a multivariate regression or other statistical analysis to predict project success using agile methodology.

[RQ14.2] For the purpose of generating workable solutions within organizations, the use of the analytic hierarchy process (Saaty and Peniwati [262][10]) is recommended to identify weights for different factors in a model for comparing different approaches.

[RQ14.3] The existing literature is focused specifically on IT projects and especially on software development. However, since the influence of agile methodology has spread much more broadly into other application areas, as illustrated by Smith [283], research is now needed to explore the trade-offs between waterfall and agile methodology for these emerging applications.

[RQ14.4] Since positive behaviors and active communication are essential to the success of agile methodology, there is a need to incorporate behavioral issues into a large-scale comparative performance evaluation of waterfall and agile methods.

[RQ14.5] Similarly, the design of hybrid methodologies for these broader application areas has not been explored, and it has the potential to deliver considerable value. For different applications, the appropriate combination of waterfall and agile components may vary.

4.15. Scalability of Agile Methodology

4.15.1. Background. The Agile Manifesto (Agilemanifesto.org [8]) proposes a new methodology for software development projects. It emphasizes the relative value of individuals and interactions over processes and tools, working software over comprehensive documentation, customer collaboration over contract negotiation, and responding to change over following a plan. Agile project planning is especially useful for nondeterministic projects, i.e., those where the final configuration of the product or service being developed is not known at the start of the execution stage and only reveals itself as a result of subsequent developments. The success of agile methodology for software development projects has led to increasingly widespread adoption in other application areas with nondeterministic projects. These areas include research and development, pharmaceutical drug development, and new product and service development.

Conboy [73] defines agility as the readiness "to rapidly or inherently create change, proactively or reactively embrace change, and learn from change while contributing to perceived customer value (economy, quality, and simplicity), through its collective components and relationships with its environment" (p. 340). However, a persistent concern about agile project management methodology has been its perceived lack of scalability (Bretz [45]). This

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[10] See also *Wikipedia*, s.v. "Analytic hierarchy process," last modified June 22, 2016, https://en.wikipedia.org/wiki/Analytic_hierarchy_process.

viewpoint is summarized by Williams and Cockburn [324], who state that agile methods "best suit collocated teams of about 50 people or fewer who have easy access to user and business experts and are developing projects that are not life-critical" (p. 40). A generic definition of scalability is that, as quantity increases, it is not necessary to change design (Bretz [45]). As discussed by Dingsøyr and Moe [88], the participants at XP 2014 workshops identify various more specific definitions of large-scale agile development. This list includes (a) over 50 developers, or 500,000 lines of code, or more than three sites; (b) over 50 persons in over 5 teams working on the same product; (c) when the principles or practices extend to other functions or business units; and (d) being at the level of the entire organization. Similarly, Power [241] distinguishes three situations: an agile team within a large organization, a large agile group within a large organization, and a large agile organization.

There are significant challenges in scaling agile methodology. Singleton [282] discusses two of them in the context of software development. The first challenge relates to iteration planning, which is difficult to coordinate except in the situation of a small, collocated team. The second challenge relates to testing for release, which is also difficult to coordinate. In the context of extreme planning, Hafterson [126] discusses three challenges of scaling agile methodology—spatial, temporal, and cultural.

Laanti [184] identifies eight components of agility that are essential for a large organization to achieve success with agile methodology: strategic agility, business agility, agile organization, people agility, tools agility, organizational culture, agility of the product, and agility to seek future value. These components imply 21 principles for scaling agile methodology. Some examples include (a) focus on content, (b) problem solving by groups, (c) continuous improvement, (d) frequent product release, (e) use of nested systems, (f) parallelization to improve throughput, (g) innovation to save cost, (h) sharing of knowledge between teams, (i) preference for speed over perfection, and (j) resolution of problems while still small.

Dingsøyr and Moe [88] identify the following as key principles for large-scale agile development:

(1) Architecture is important in determining how work is coordinated.

(2) The levels of change and uncertainty influence how architecture work is organized.

(3) Common norms and values facilitate interteam coordination.

(4) Effective knowledge networks are essential in large-scale development.

(5) Continuous feedback from the portfolio to the product level enables decisions that are consistent with agile portfolio goals.

(6) Continuous feedback is given from the project to the portfolio level, to enable optimization of the portfolio.

(7) Understanding the need for agility and what is the required scale is important.

(8) Agility should scale with respect to both the number of teams and the activities in each iteration.

Scrum (Schwaber and Beedle [271][11]) is a practical framework for implementing agile principles. An engaging introduction to Scrum is provided in Shojaee [280]. An informal description of a Scrum process (Singleton [282]) is that a team meets for a short planning session and decides what they will work on in the next iteration. They then work for a fixed period of time, which is typically between one and three weeks, to deliver a version of their product that is potentially releasable to users for feedback. To achieve this, Scrum defines several artifacts that enable agile performance. These include product backlog, spring, sprint backlog, sprint burn-down chart, and release burn-down chart. Kanban[12] is a planning system for lean production, originally developed for Toyota Motor Corporation (Ohno [222]). A Kanban system establishes an even workflow and limits work-in-process inventory in a

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[11] See also *Wikipedia*, s.v. "Scrum (software development)," last modified July 31, 2016, https://en.wikipedia.org/wiki/Scrum_(software_development).

[12] *Wikipedia*, s.v. "Kanban," last modified July 20, 2016, https://en.wikipedia.org/wiki/Kanban.

manufacturing system. The key principles of a Kanban system are the use of a pull system for work, continuous rather than batch design of work, and lean operation without inventory. A big difference between Scrum and Kanban is that in Scrum work is divided into sprints that last a certain amount of time, whereas in Kanban the workflow is continuous.

However, there is apparent value in combining the principles of Scrum and Kanban systems as a means to improve scalability. Singleton [282] recommends the incorporation of Kanban principles into Scrum to overcome the challenges of scaling agile methodology. This can be achieved by planning releases at the end of a sprint, rather than as conventionally within Scrum at the beginning. The usual sprint planning step is removed, which saves time, and when the release date arrives, whatever is ready is released. Scrumban[13] is a software development model that integrates features of both Scrum and Kanban. It is most suited for projects with frequent and unexpected work items or programming errors. There are no set limiting values for unfinished work (Kniberg [173]).

4.15.2. Future Research. Because of the growing influence of agile project management, there are several important topics for further research into how to scale this methodology to larger projects. Several such topics appear in a research agenda compiled at XP 2014 workshops. These include the first five listed below:

[RQ15.1] Identifying what factors are important influencers of the development process in large projects

[RQ15.2] Coordinating work between teams in large projects

[RQ15.3] Identifying appropriate metrics to monitor progress and support transparency

[RQ15.4] Ensuring feedback for learning, use of knowledge networks, and learning practices

[RQ15.5] Coordinating and prioritizing requirements, and ensuring continuous delivery

[RQ15.6] More generally, developing guidelines for scaling agile methodology for new application areas such as new product and service development (Smith [283]) with very different characteristics—the procedures used for software development will apparently need to be modified for other applications

4.16. Availability of Data

Because of the worldwide prevalence of project management as a business process, the research data requirements of project management differ from those of many business applications. This point can be illustrated as follows. If you are studying the power system of New York City or the Metro transit system of Washington, D.C., then there is one potential user or client for the results of your work; certainly, you need data from them. By contrast, project management has a million potential users, each with different data. Hence, some representative real world data is highly useful, and expanding and generalizing it with some randomly generated data provides a broader and more robust perspective. Fortunately, as discussed below, both these options are now readily available.

The need for project management data has long been recognized. Elmaghraby and Herroelen [99] mention the need for project data sets that span the full variety of factors which influence project complexity. Project management data can be either empirical (i.e., real world) or artificial (i.e., randomly generated). Apparently, the first project control study to use real world data is that of Bright and Howard [46]. Vanhoucke et al. [312] summarize the requirements, sources and types of project management data, and provide an overview of how it can most effectively be obtained. They identify a strong preference outside the academic community for empirical over artificial data. However, their reluctance to support this perspective, due to fundamental problems that frequently arise with empirical data, is also supported here.

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[13] *Wikipedia*, s.v. "Scrumban," last modified July 19, 2016, https://en.wikipedia.org/wiki/Scrumban.

An important distinction that arises within project management data is that between static and dynamic data. Static data consists of all the information that is needed for project planning before execution begins. This category includes task definitions, precedence relationships, and estimates of time and cost. Dynamic data includes tracking data on the realization of uncertain quantities such as task durations. However, reliable dynamic data is harder to access than reliable static data, for two reasons. First, it tends to be collected at irregular intervals during execution. Second, it tends to be difficult to separate from the effects of management decisions such as resource reallocations. Consequently, it is difficult for a researcher to identify causal relations that affect the performance of solution procedures and enable comparisons between those procedures. Hence, if a research study calls for dynamic data, it is necessary either to review empirical data critically or to resort to the use of artificial data.

An overview of the history and current availability of empirical project management data is provided by Batselier and Vanhoucke [29], who document the construction of a large and varied empirical database. They summarize the 11 previous works that use real-world data to study more than 120 projects, to which they add data for 51 projects originating from 47 different organizations. They also contribute to the future development of project management data, by recommending a "project card" data collection format which structures the review of received data for its completeness and authenticity. The extensive and varied empirical database established by Batselier and Vanhoucke [29] is available online (OR-AS [225]).

An important advance to support the availability of artificial data is the development of PSPLIB, a project scheduling problem library, by Kolisch and Sprecher [177], based on the early random network generator ProGen (Kolisch et al. [178]). A general principle is that, if artificial data is to be used, then it should be based on a controlled and full factorial design (Vanhoucke et al. [312]). More recently, the most widely used random generator for artificial project management data is RanGen, as described by Demeulemeester et al. [84]. The format of RanGen allows the user to control various characteristics of the instance, including the number of tasks, the density of the precedence graph, the shape of the graph relative to serial and parallel configurations, and several features related to resource usage and availability. An important advantage of RanGen is its ability to generate a complete range of relevant project networks.

The need for data for two important generalizations of classical project scheduling is addressed in recent developments. The first generalization is data generation for multi-mode projects, under which some or all of the tasks may be performed in various ways with different durations and resource requirements. Van Peteghem and Vanhoucke [306] develop a new data set for this problem, and demonstrate that it achieves greater range and variety in the instances generated than previous data sets do for this problem. The second generalization is data generation for multiple projects that share resources, Browning and Yassine [51] describe a network generator for this problem, and provide over 12 thousand test instances from a full factorial experiment.

It should be remembered that, while both empirical and artificial data are potentially valuable and relevant, they serve different purposes. Empirical data establishes relevance to practical projects. Artificial data enables the convenient testing of solution procedures against a wide variety of well controlled scenarios, but needs to justify that it is realistic. As Vanhoucke et al. [310] comment, "A stronger synergy between empirical data and artificial data is necessary to increase the realism of research experiments" (p. 19). Moreover, this is of greatest importance for dynamic data. Nonetheless, the overall availability of data for project management research is already sufficient for most research purposes, and is still rapidly improving.

5. Teaching Opportunities

Section 5.1 discusses the importance of teaching project management. In Section 5.2, we identify some of the most important and useful ideas from the literature of teaching project management. Sections 5.3 and 5.4 discuss the advantages and challenges, respectively, of teaching project management. A list of topics for a typical graduate-level project management course is presented in Section 5.5. Section 5.6 describes a variety of games and exercises that provide hands-on learning experiences in a course. Section 5.7 describes several videos that integrate project management experience and consulting advice into classroom material to support lecture material. Finally, Section 5.8 describes a possible design for a graduate professional course in project management.

5.1. Importance of Teaching Project Management

Project Management Institute [246] makes a compelling case for teaching project management, based partly on some impressive statistics. Not only is the annual value of projects about \$12 trillion, but the amount of value annually at risk from a deficiency of well-trained project managers is \$4.5 trillion. As much as 30% of the current project management workforce is estimated to become eligible for retirement during the next 10 years—hence, the forecast availability of 15.7 million new jobs in project management by 2020. According to Project Management Institute ([241], p. 2), a 2008 survey by Economist Intelligence Unit establishes that 97% of the skills needed for a successful business career fall within the scope of project management. More than 60% of the respondents indicate that project managers communicate directly with senior managers in their organization and, furthermore, that this percentage is likely to increase. The number of degree programs in project management in China increased from 1 in 2003 to 103 in 2008. The urgent need for more project managers is summarized by Project Management Institute [246] as follows: "Organizations are relying upon educational institutions like yours to meet this need. Only you can educate the skilled graduates that they are waiting to hire and perform the research needed to advance this vital discipline" (p. 2).

5.2. Teaching Literature

We briefly review the literature of teaching project management. Because of the variety of possible teaching environments—for example, academic undergraduate, graduate professional, and vocational—it is not possible to recommend one delivery model for all situations. Instead, brief descriptions of several useful sources of information about teaching project management are provided.

- Extensive resources for teaching project management are provided by the Project Management Institute [247].
- A collection of links to useful sources for teaching project management is provided by Amarillo College [12].
- Ojiako et al. [223] survey students in project management courses about their learning experiences. One of their main conclusions is that students of this topic need to become creators of knowledge rather than merely recipients of it. To this end, they recommend that students be encouraged to become proactive problem solvers and critical thinkers.
- Geist and Myers [112] review a variety of methods used for teaching project management. They recommend a combination of lecture-based and activity-based learning, along with group projects. The advantages of both simulated and real-world projects are discussed. Also recommended, although a less active learning method, is the use of case studies.
- Abernethy et al. [2] make a case for an experiential approach to teaching project management, based on an argument that the necessary tools and techniques only become meaningful when applied. The recommended approach involves having students work on real-world projects.

- Hood and Hood [152] recommend the use of project simulations for teaching the management of software projects. They describe in detail a LEGO bridge-building project to teach students how to measure progress and manage change.
- Shinkins [278] describes the development of, and experiences with, a computer-based training package, Project Inceptor, for project management. Feedback from the use of the package is reported as substantially positive.
- Poston and Richardson [240] describe a course in which project management professionals provide guest lectures, serve as mentors for class projects, provide real-world projects for class analysis, and judge student competitions.
- Mengel [207] documents the importance of integrating project management into a leadership curriculum.
- The advantages and challenges of using online courses to teach project management are discussed by Tabatabaei [293].

The following advice from the project management teaching literature provides a balanced view with which we are in complete agreement:

> In order to establish a set of best practices for teaching project management, a complementary blend of theory and activity based learning techniques should be utilized. Traditional classroom lectures may be best suited for transferring conceptual knowledge but must be kept stimulating in order to maintain the student's interest. Guest speakers can be incorporated to demonstrate real life scenarios. Team-building activities can lead into, or reinforce, a lesson's concepts. Novel scenarios such as game playing or the introduction of entertaining literature may assist in demonstrating the application of theory. (Geist and Myers [112, p. 206])

5.3. Advantages

The first advantage of project management as a teaching topic is that most potential students enter your course already recognizing it as an important business process. For those that do not, it is easy to provide the available statistics—for example, the fact that one-fifth of the world's economic activity is conducted as projects. By the end of your course, there should be very few students who fail to see the importance of the topic or how it might be relevant to their future business career.

Another advantage of teaching project management is the unusual variety of content style. Some topics within a typical project management course are quite technical. For example, PERT and Monte Carlo simulation make use of statistics. The usefulness of network algorithms, as documented by Ludwig et al. [198], can be discussed. Many instructors use linear programming models to evaluate crashing trade-offs. On the other hand, communication and motivational issues (for example, the communication parables of Kerzner [168]) need to be discussed. Critical chain project management requires justification from the prevalence of Parkinson's law, which leads into a discussion of behavioral issues and incentives. This variety of content style distinguishes a project management course from most others in business or engineering. For many students, this makes the topic unusually interesting. It also gives the appearance of a "level playing field" where students from various backgrounds can compete without obvious advantage or disadvantage.

The third advantage of teaching project management is the potential for extensive class discussions on many topics. While there are certainly ideas and issues that are unique to project management, quite a few topics within project management can be discussed in a constructive way from "business commonsense" alone. An example is the issue of whether to construct a project budget from the top down based on senior management input or from the bottom up by the aggregation of information from the task level. The relative advantages of each can be discussed in detail from general business principles. Similar comments apply to several topics within project risk management.

The availability of numerous illustrative and entertaining "war stories" about project management provides an additional advantage. Projects are typically evaluated based on their time, cost, and scope performance relative to expectations. There are many well-known stories of spectacular failures in this respect. There are also a few impressive success stories, such as the freeway reconstruction project by C.C. Myers after the 1994 Northridge earthquake.[14] Moreover, some iconic projects had poor outcomes based on the usual performance metrics but are now viewed as successful—the Sydney Harbor Bridge and the movie *Titanic* are two examples. A discussion of project crashing techniques may also include the following entertaining story. During the making of the movie *Mogambo* (1953), producer Sam Zimbalist reminded the director, John Ford, that the filming was running late; Ford responded by tearing three pages from the script, replied, "We're on schedule," and never filmed those pages.[15]

A fifth advantage of teaching project management is the availability of guest speakers. Every business community has numerous project managers, and since their job is (by their own definition) all about communication, they typically make very good guest speakers for class. Bringing guest speakers to the classroom, to discuss success and failure stories about implementation of the project management principles covered in lectures, adds substantial credibility to the course and to the instructor (Geist and Myers [112]).

Another advantage of teaching project management is the availability of numerous games, simulations, competitions, exercises, and videos about the various topics in the course (see Section 5.6). Hands-on learning, either individually or in groups, is both informative and entertaining, particularly when student groups become competitive. Also, well-chosen videos vividly illustrate the cultural and communication issues of project management in the workplace, which is especially helpful to students with less business experience (see Section 5.7).

Another advantage of teaching project management is that this topic is greatly underserved in both business and engineering schools. College-level accreditation reviews frequently mention the importance of project management as an elective, or even required, course. Yet it is quite rare for project management courses to be taught by tenure track faculty. Doing so provides the opportunity for substantial impact in the classroom and also speaking opportunities within the business community, as well as executive education and consulting opportunities.

A final advantage of teaching project management is the opportunity to observe project management issues that may evolve into research topics.

5.4. Challenges

The first challenge of teaching project management is the exceptional diversity in students' backgrounds. This comment relates to the students' ages, technical backgrounds, and amount of related work experience. Because of the wide variety of programs from which students may enroll in a project management course, this variety is unavoidable. It is frequently the case that a 35-year-old American student with 10 years of project management experience and Project Management Professional (PMP) certification is sitting next to a 22-year-old student from China with an engineering degree and no work experience. The course needs to be accessible and interesting, and provide reasonably fair access to good performance outcomes, to both these students. This challenge needs to be addressed, but doing so requires a nonstandard teaching approach that relies substantially on active learning and less on standard Project Management Body of Knowledge (PMBOK) (Project Management Institute [245]) or textbook material.

The second challenge is students' misconceptions about the topic and, therefore, also about the course. Some students view such a course as focusing mainly on how to motivate the project team or resolve the concerns of the project owner. While such skills are, no doubt, of value to a project manager, they are best taught as part of a course in a management

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[14] *Wikipedia*, s.v. "C. C. Myers," last modified March 25, 2016, https://en.wikipedia.org/wiki/C._C._Myers.

[15] *Wikipedia*, s.v. "John Ford," last modified August 1, 2016, https://en.wikipedia.org/wiki/John_Ford.

department. Such a course may have a title such as "Communication and Leadership" or "Change Management." Students for whom these issues are their main interest can easily be redirected to such a course.

The third challenge relates to students' backgrounds and abilities with software. For students coming from programs without strong computer requirements, getting started with project planning using Excel and Project represents a significant challenge. For Project especially, the initial setup of a project can appear quite complicated to students without computer experience. For some students, it may even deter them from taking the course, which would be unfortunate. Substantial support, in the form of software tutorials, needs to be provided. These tutorials provide line-by-line instructions for developing spreadsheets for project planning.

Another challenge is exam logistics. Students will need coursework and exam lab access to Microsoft Office software including Project, as well as a course management system with a dropbox for uploading output files and other solutions.

The fifth and final challenge is finding a classroom that is large enough for all the students who will want to enroll in your project management course!

5.5. Topics

In this section, we consider each of the topics that might be offered in a typical graduate professional course on project management. The topics covered approximately follow the structure used in the textbook by Klastorin [170].

0. *Preliminary*
    - Warm-up questions to resolve common misunderstandings about project management
    - Motivate the topic with statistics about its importance
    - Outline the course, including the importance of the in-class and online exercises and guest speaker events
    - Thinking challenge about a simple project (e.g., office move)
    - Discuss Project Management Institute and Project Management Professional
1. *Introduction*
    - Project definitions, roles, and perspectives
    - History and importance of project management
    - Project management within a business context
    - Self-assessment exercise on project management roles and conflicts (in-class, template)
    - Video on introductory project management with a construction project example
    - Project management maturity model
    - Reasons why projects succeed or fail
    - Video on why projects fail
    - Guest speaker on general project management and career issues
    - Project management maturity model
2. *Project Evaluation and Selection*
    - Individual versus portfolio selection
    - Net present value and internal rate of return
    - Probabilistic events and expected commercial value
    - Zero-one knapsack model for project selection
    - Multifactor scoring model for combining quantitative and qualitative data
    - Work breakdown structure
    - Exercise on designing a work breakdown structure for the activities of the course
    - New product development projects
3. *Project Organization*
    - Communication issues and proverbs
    - Group harmony and project performance

- Arguments for and against autonomy
- Autonomy-level design exercise (in-class, template)
- Project management office
- Video on project management office
- Big data performance analysis (in-class, statistical exercise)
- Practical advice about subcontracting

4. *Scheduling*
    - Precedence, activity on node, and activity on arc networks
    - Different types of slack
    - Online simulation exercise: triple constraint trade-offs (Austin [20])
    - Project scheduling as a linear program
    - Introduction to Microsoft Project
    - Guest speaker on IT project management
    - Multitasking exercise (in-class, template)
5. *Budget and Cost*
    - Functions and components of a budget
    - Choices between top-down and bottom-up budgeting methods
    - Timing flexibility and net present value maximization
    - Fast tracking, crashing, and time/cost trade-offs
    - Project crashing game (in-class, template)
6. *Uncertainty, Critical Chains, and Agile*
    - Uncertainty in task times
    - Parkinson's law and Student syndrome
    - PERT and Monte Carlo simulation
    - Critical chain project management
    - Video on critical chain project management
    - Agile project management
    - Video on introduction to agile
    - Online simulation exercise: disrupted projects, prototypes, and agile (Austin [20])
    - Video on Scrum implementation of agile
    - Guest speaker with in-class exercise on agile
    - Video on difficulties of implementing agile in a traditional project-planning environment
    - Extreme project management
7. *Risk Management*
    - The value of information
    - Tornado diagram and sensitivity chart
    - Preventive and contingency risk management
    - Video on project risk management
    - Insuring against risk
    - Risk management in-class online exercise (Norway University of Science and Technology [221])
    - A world-class consulting report on risk management, with an example application
8. *Resource Management*
    - Why considering resources makes planning harder
    - Microsoft Project, resource leveling, and resource allocation
    - Developing heuristics for resource leveling and resource allocation with Microsoft Project
    - Video on project resource management
    - When to team resources
9. *Monitoring and Control*
    - How, and how much, to monitor

- Earned value management and performance metrics
- Estimating the earned value
- Video on earned value management
- Boondoggles and issues in closing a project

10. *Managing Multiple Projects*
    - The complexity of managing multiple projects
    - Allocating resources between projects
    - Practical guidelines for managing multiple projects
    - Multiple projects management game (in-class, template)

5.6. Games and Exercises

There are numerous games and exercises that support a graduate course on project management. These are available online and/or from their authors. These activities provide valuable hands-on learning experiences and a chance for students to develop their creative problem-solving skills. They also provide a change of pace from the lecture material and are often entertaining as a result of students' tendency to be competitive with each other. The following selection of hands-on activities provides effective coverage of the various course topics listed in the previous section.

(1) *Creative problem-solving skills exercise.* This questionnaire-based exercise enables students to assess their own project management skills, identify where they would find most satisfying work within a project, and understand how conflicts naturally arise with other project team members. Although the outcomes from the exercise show some correlation with those from the Myers–Briggs Type Indicator,[16] the focus in interpreting the results is on identifying detailed problem-solving styles rather than on general personality types.

(2) *Harvard Business School (HBS) online simulation* I. The first HBS simulation considers a relatively straightforward project without unexpected or problematic developments, but with the need to balance the three issues of time, cost, and scope. Decisions are made for each simulated week, and performance graphs show progress, cost, and project team morale. Students are permitted an unlimited number of attempts and given hints about how to search over a highly nonconcave return function.

(3) *Performance analysis exercise.* This exercise uses a large data set for construction projects in the Washington, DC area. Groups of students, acting in the role of a project management office, are expected to perform statistical analysis on the data set in order to identify underlying causes of the observed performance. The most useful statistical techniques are analysis of variance and hypothesis testing. The reports generated are presented to the class at the end of the exercise.

(4) *Work breakdown structure exercise.* Groups of students are given the task of designing a work breakdown structure for the activities in the course from the student side, based on the information in the syllabus. The results typically show a variety of interesting breakdown structures—for example, based on individual versus group work, on the type of assignment, or on the chronology of course events. Results can be displayed and discussed.

(5) *Project autonomy design-level exercise.* Groups of students are asked to design an appropriate level of autonomy, ranging from a functional project through matrix options to a project team, for given organizational and project data. Results are collected after each round so as to build a consensus. Groups should be asked to justify their final recommendations. The results will vary because of interpretation and appetite for risk.

(6) *Project crashing competition.* Students are given a project network with standard task times. Three additional workers can be allocated to the tasks, and subject to some constraints, they can also be reallocated to later tasks, which reduces the task times and

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[16] *Wikipedia*, s.v. "Myers–Briggs Type Indicator," last modified July 27, 2016, https://en.wikipedia.org/wiki/Myers%E2%80%93Briggs_Type_Indicator.

potentially the project makespan. The number of combinations of worker assignment is large. Students can typically develop good intuition and good heuristics about which tasks to crash.

(7) *Harvard Business School online simulation* II. The second HBS simulation is a chaotic project scenario with staffing losses and a shortened deadline as a result of the unexpected release of a competitive product. Students are permitted an unlimited number of attempts and encouraged to try the use of prototypes.

(8) *Norwegian University of Science and Technology online risk management game.* This online game is played in class. After a practice round, groups of students are asked to make resource allocation and risk mitigation decisions for a small project. The cost and delay of using mitigation are known, but the probability and effect of an unmitigated event are not. The intuition gained includes the fact that resource allocation and risk mitigation decisions should be coordinated with each other.

(9) *Multiple projects management game.* This game, developed at Case Western Reserve University, is played in groups of three or four. The challenge is to schedule three projects with three resources, each of which is needed for some tasks on all projects. The work completed in any period is simulated from online dice. In the first round, groups apply a priority approach as a benchmark. In the second round, groups apply a strict multitasking approach, i.e., rotating between the available projects, as a benchmark. In the third round, groups can use any combination of priority rule they like to beat the two benchmarks. A critical chain approach is usually among the most successful and substantially better than the benchmarks.

5.7. Videos

This section briefly summarizes the content of 10 videos that support the course.

1. "Alton Bridge" (12 m 52 s)

Introduction to project management challenges and terminology using a large public construction project

2. "The Truth About Project Failures" (9 m 05 s)

Consulting company video about the variety of things that can go wrong in project management

3. "The Project Management Office" (9 m 19 s)

Consulting company video about good and bad project management office practices

4. "Critical Chain Project Management Overview" (9 m 32 s)

Problems with traditional critical path methodology that motivate a critical chain approach and how such an approach can be implemented

5. "Agile Project Management Overview" (6 m 55 s)

Introduction to agile project management, including benefits and implementation procedures

6. "Scrum in Under 10 Minutes" (8 m 00 s)

Detailed explanation of the Scrum implementation system for agile project management, including its artifacts

7. "I want to Run an Agile Project" (9 m 50 s)

Dramatization of the difficulties faced by the manager of an agile IT project when faced with organizational constraints and bureaucracy

8. "Project Risk Management" (9 m 50 s)

A video presenting a simplified view of how to handle project risks, using a five-step process: identify risks, filter risks, quantify risks, plan responses, and control risks

9. "Resource Based Scheduling" (4 m 38 s)

A look at the impact of resources on a project schedule, showing how to manage resources heuristically

10. “Earned Value Lite: 10 Steps to Successful EVM” (7 m 20 s)
A video providing a simplified introduction to earned value analysis

5.8. Example Course Design

This section describes the design of a 14-week, 42-classroom-hour graduate business elective course in project management, typically offered in multiple sections with up to 70 students in each. The backgrounds of students enrolling in a project management course at Fisher College are typically as follows: full-time MBA students (25%), part-time MBA students (25%), joint business–engineering programs (20%), accounting (6%), management (4%), medical sciences (M.D./Ph.D.) (4%), healthcare management (4%), pharmacy (PharmD) (4%), science (4%), and others (4%). Their ages typically range from 21 to 40.

Evaluation of Performance
Case reports (by study groups): 4 @ 40 = 160 points
Case presentation (by study groups): 1 @ 40 = 40 points
HBS online simulation exercises (individually): 2 @ 20 = 40 points
Class participation (individually): 1 @ 40 = 40 points
Final exam (individually): 1 @ 120 = 120 points
Total = 400 points.

Class Participation
Attendance at guest speaker events: 3 @ 5 = 15 points
Participation in creative problem-solving skills exercise and multiple projects management game: 2 @ 5 = 10 points
Performance analysis exercise and risk management game: 2 @ 4 = 8 points
General participation: 7 points
Total = 40 points.

Exam Format
Three-hour exam, all materials open
Exam lab, with availability of Microsoft Word, Excel, and Project
One hundred points on project planning, scheduling, and monitoring questions, using spreadsheets
Twenty points on short-answer, general project management knowledge questions.

Case Analysis Format
Limit of three-page case reports, with unlimited additional appendices
Fifteen-minute presentations, followed by up to 10 minutes of questions from the class and instructor.

6. Concluding Remarks

This work provides a discussion of research and teaching opportunities within project management. The research opportunities arise from several sources. The first source is industry’s increasing focus on new project management applications with characteristics that differ greatly from those of traditional applications. The second source is the development of new methodologies that have evolved from project management practice but are not yet well supported by academic research. The third source is a considerable underestimation of the value of project management as an interesting research area over the last 20 years. This in turn has caused research to lag behind recent business innovation and the growing range of applications. Also because of this underestimation, there has been little Ph.D. education in project management for the last 20 years, and hence few new researchers have entered the project management field. Also, leading academic journals in operations research/operations management (OR/OM) have published few articles on project management in the last 20 years, compared with other topics of comparable practical value and research potential. On the teaching side, many university courses in project management are taught by part-time or clinical faculty or by local project managers. These instructors are frequently highly engaging and motivational for students, but it is difficult for them to integrate recent research developments into the classroom. Therefore, from the perspective of content, it would clearly be beneficial for more courses, especially at the graduate level, to be taught by research-active faculty members.

The open research problems described here and in Hall [129, 130] require a wide variety of analytical techniques, including robust optimization, network analysis of WBS structures, multiple regression and other statistical analyses, nonlinear optimization, noncooperative game theory, mechanism design, competitive and strategic behavior, empirical studies, and stochastic analysis of project networks. This variety itself presents an interesting challenge to researchers. There are also important recent improvements in the availability of data for research on project management.

Over the next 20 years, emerging trends within the practice of project management will identify further important research questions besides those discussed here. One of the most financially significant is understanding to what extent agile project management methodology can be effective for applications outside the range for which they were originally developed. It is unlikely that agile methodology will come to be used routinely for highly deterministic applications such as construction and engineering. However, there is a range of applications with a mixture of deterministic and nondeterministic characteristics for which agile methodology may be useful. The natural application area to consider within this range is new product and service development. Some interesting practical discussions about the potential for agile methodology to be applied in this context appear in Smith [283]. The research issues that support such trends will crystallize over time.

Several conclusions can be drawn from this work and the related business and academic literature:

(1) We identify the following trends making project management harder: increased competition, shorter product and service life cycles, tighter budgets, unfamiliar and more complex applications, and globally distributed and multicultural project teams.

(2) By contrast, several trends are making project management easier: better project management training, publication of best practices information, and better software support. The relative impact of this effect and the previous one varies from application to application.

(3) Underestimation of the value of project management as a planning methodology over the last 20 years has led research to fall behind recent business innovation and the growing range of applications.

(4) Important recent developments on the business innovation side of project management are not yet well supported by research.

(5) Leading journals in OR/OM have published few articles on project management in the last 10 years, compared with other topics of comparable practical importance or value.

(6) Practice and research have diverged, and relative to the value of the applications considered, few new researchers have entered the project management field.

(7) There are numerous available teaching opportunities for project management courses, and such courses are highly interesting and rewarding to teach.

In conclusion, we expect that the next 20 years will see many important advances in academic research on project management and that such advances will greatly improve the practice and teaching of the challenging business process of project management. Hence, the overall conclusion of this work is that numerous interesting research and teaching opportunities in project management will be available for many years to come.

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