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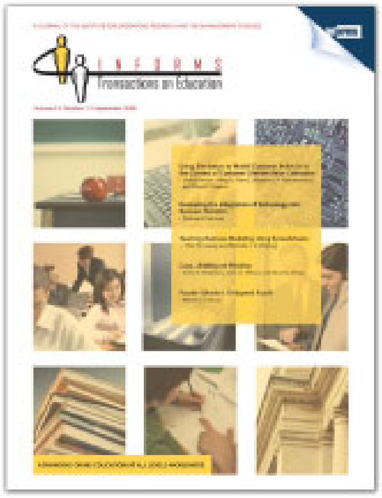

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Teaching Critical Chain Project Management: The Academic Debate and Illustrative Examples

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In recent decades, the project-scheduling practice known as critical chain project management (CCPM) has been successful in industrial applications, yet remains a subject of disagreement among scholars and is only sporadically taught in business schools. The purpose of this paper is to assess what aspects of CCPM are appropriate in operations courses, whether dedicated project management classes or broader introductory operations management classes. To answer this, we survey academic literature on traditional project management problems that gave rise to CCPM to understand if these issues are real. We also examine whether the CCPM methodology should, according to scholars, correct these problems, and survey project success stories attributed to CCPM. We conclude that CCPM is an appropriate project management methodology for student consideration on the basis of motivating critical thinking—especially about behavioral issues—rather than on formal scientific proof of its merit. In so doing, we survey teaching resources as well as articles in the trade press on the subject. We then present a sequence of numerical practice problems that are designed to motivate further critical reflection about CCPM. Throughout are a number of open questions about CCPM that the academic community has not yet answered and that instructors should keep in mind.

Key words: teaching project management; teaching management science; teaching operations management; developing analytical skills; developing critical thinking skills; interdisciplinary teaching
History: Received: December 2009; accepted: August 2011.

1. Introduction

In traditional project management practiced in most industries and taught in most business and engineering schools, it is assumed that a sequence of tasks in a single project defines the critical path. In critical chain project management (CCPM), however, a sequence of resources, called a *critical chain*, may require a task sequence that can exceed the critical path's duration. To account for a project's critical sequence, scholars and practitioners introduced resource-constrained project-scheduling methods, perhaps as early as Wiest (1964). However, compared with traditional critical path methods, CCPM has three fundamental differences: cultural changes in milestone accountability and thus task duration estimation, the employment of safety buffers, and the elimination of multitasking and resource conflicts (Watson et al. 2007).

The CCPM methodology was born out of the so-called theory of constraints (TOC) for capacity planning (Goldratt and Cox 1984). According to Watson et al. (2007), TOC-based project management was introduced at the 1990 International Jonah Conference and became better known after Goldratt's (1997) *Critical Chain*.

Goldratt's novel was reviewed in both the business and academic presses (e.g., McKay and Morton 1998, Elton and Roe 1998, Rand 1998) and inspired dozens of practitioner-oriented articles and books (e.g., Newbold 1998; Patrick 1999; Pinto 1999; Globerson 2000; Maylor 2000; Parr 2000b; Piney 2000; Simpson 2000; Steyn 2000b; Wilkens 2000; Hutchin 2001; Patrick 2001, 2002; Scherschel 2002; Sood 2002; Nokes et al. 2003; Sood 2003; Gupta 2008; Newbold 2008; Kishira 2009a; Gupta 2010). More recently, CCPM was summarized in Cox and Schleier (2010). As we survey in §3, these authors and others attributed astonishing improvements to CCPM in all sorts of organizations, including some of the most notoriously difficult project environments such as R&D and software development.

As CCPM gained exposure and acceptance, scholars examined its merits. See, for example, Rand (2000),

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Shou and Yeo (2000), Steyn (2000a, 2002), Herroelen and Leus (2001), Maylor (2001), Herroelen et al. (2002), Raz et al. (2003), Cohen et al. (2004), Lechler et al. (2005), Trietsch (2005), Watson et al. (2007), Balakrishnan et al. (2008), and Stratton (2009). Consultants embraced the methodology, and new project planning software tools followed. We survey such tools in §4.6.

CCPM gained traction in higher education. Pedagogically, it is praised for motivating critical thinking about the potential ills of traditional project-scheduling and planning methods. Other advantages include bringing student attention to overlooked behavior issues, resource contentions, and multiple project environments. Because CCPM is about project planning and execution, it complements the broad range of topics that occupy a project management class (i.e, the strategic value of selecting the right projects, project budgeting, etc.).

If one believes in the merits of CCPM and wants to introduce it to undergraduate and/or graduate students, the first problem is selecting supporting materials. Although some operations management textbooks now acknowledge CCPM in footnotes and sidebars (see, for example, Jacobs and Chase 2011) and some texts are dedicated entirely to CCPM (e.g., Newbold 1998, Leach 2005), we are aware of no textbook that systematically presents CCPM with examples, exercises, case studies, and scientific references the way such resources exist for teaching traditional project management methods. That said, we find the resources summarized in Table 1 useful for pedagogical purposes.

One can combine these resources in various ways depending on course needs and available time. For example, in a core introductory operations class we have simply assigned Elton and Roe (1998) and offered extra credit to students who read and discuss (Goldratt 1997). At the other extreme, a three-credit project management class, we have required Goldratt (1997), Newbold (1998, Chap. 8), run the multitasking game in class, shown Jacob's (1998) video, and required some of the exercises given in §4.

Table 1 **Resources for Teaching Critical Chain Project Management**

Reference	Description	Approx. time
Elton and Roe (1998)	"Light" overview	30 minutes
Newbold (1998, Chap. 8)	Numerical example of CCPM	60 minutes
Budd and Cerveny (2010)	Technical overview	90 minutes
Multitasking game	In-class game with debriefing	120 minutes
Goldratt (1997)	Business novel; in-depth motivation of CCPM	10 to 15 hours
Newbold (1998)	Detailed guide to implementing/applying CCPM; a companion to Goldratt (1997)	10 hours

Regardless of how one combines any materials to present CCPM, one purpose of this paper is to address the mixed academic opinion about critical chain scheduling and buffer management. For instance, one concern is that the notion of a critical chain is not new, attributable to Wiest's (1964) critical sequence (Herroelen and Leus 2001) and a project buffer to O'Brien (1965) (Trietsch 2005). Others feel that some aspects of CCPM are simply not empirically justified, or worse, contradict well-accepted scheduling research (Herroelen and Leus 2001, Herroelen et al. 2002, Raz et al. 2003, Trietsch 2005). We summarize these issues and suggest appropriate classroom approaches to addressing them.

In addition to scholarly criticism of CCPM, there is a divide between traditional PERT/CPM methods and CCPM. Some feel CCPM does not properly complement currently accepted project management practices, and in so doing, poses an unnecessary methodological choice between CCPM and mainstream practices (Raz et al. 2003). "There is a variety of such methods some of which are mutually incompatible and attempting to describe them all is likely to cause confusion" (Nokes et al. 2003; see p. 26 for a comparison of nine differences). And it is our experience that students ask, "Why do you teach PERT when we learn so much from *Critical Chain*?" We report how we come to terms with this potential divide in our classes. For example, in §4.3 is an activity that we use to encourage students to puzzle over the differences between a PERT and CCPM schedule.

The purpose of this paper then, in summary, is to give teachers insights about adopting CCPM in a balanced fashion, given that much of what has been written about the method has not been peer reviewed. It is intended for professors who are not necessarily experts in the literature of project management or scheduling theory, but are often asked to guide students in a unit on project management.

We assume that the reader has read Goldratt (1997) or is at least mildly familiar with CCPM. If not, alternatives include the brief chapter-by-chapter summary in Woeppel (2005), the overview of Budd and Cerveny (2010), and the examples in Newbold (1998), especially Chapter 8. One of the authors uses these ideas in a stand-alone project management course; the other uses the ideas in MBA and undergraduate introductory operations management, where at least three sessions can be devoted to the topic.

The paper proceeds as follows. First, in §2 we define CCPM, identify the ills of traditional project management that motivated it, survey related academic literature to understand if these are real concerns, and suggest strategies for sharing this information with students. In §3, we ask if CCPM

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works, survey the growing number of trade articles that say it does, and ask why there is little peer-reviewed literature to the same effect. In §4, we momentarily accept CCPM and develop a sequence of simple numerical examples that are intended to motivate critical student thinking about the CCPM methodology. Two are designed to practice resource-constrained project scheduling. The third requires students to reformulate a classic PERT/CPM problem as a CCPM schedule to highlight differences in the methodologies. The fourth is a simple example in which resources are constrained across multiple projects. At the end of §4 we summarize games, simulations, and other exercises that others have developed for teaching CCPM and resource-constrained project scheduling. We conclude with our thoughts on CCPM in the classroom.

2. Origins and Performance of CCPM

Because CCPM was proposed as a solution to traditional project management's supposed shortcomings, it is worth asking if scientific evidence in peer-reviewed journals (a) justifies these motivations and (b) agrees with the prescribed solutions that underpin CCPM.

Before answering (a), it is useful to define the reasons behind CCPM more precisely. Because we recommend introducing students to CCPM through Goldratt (1997), our notion of CCPM is rooted in its use there, but we acknowledge that subtle variants can be found in Newbold (1998), Nokes et al. (2003), Leach (2005), Walker (2010), and others. We summarize the motivating factors and their prescribed solutions in Table 2.

Realization Technologies, Inc. expresses the proposed CCPM solution in different words. According to Gupta (2008, 2010) and Jensen (2010), a critical chain schedule is one that (a) limits the number of simultaneous projects (and hence multitasking) with staggered starts, (b) creates aggressive project plans with global buffers, and (c) avoids precise schedules and instead gives highest priority to tasks that consume the most buffer. Notice that (a)–(c) are a subset of the "Proposed CCPM Solution" column, Table 2.

Let us now consider if project management scholars agree with the elements of Table 2, in order.

Table 2 Motivations for CCPM

Traditional project mgmt	Proposed CCPM solution
Safety time is imbedded in individual tasks	Reduce task time estimates; pool safety time in project and feeding buffers; eliminate accountability of intermediate milestones and change the activity time estimation culture.
Parkinson's Law causes delays	Move safety time from individual tasks to project and feeding buffers.
Parallel activities are underappreciated	Insert feeding buffers where noncritical sequences join critical chain.
There is an early vs. late start dilemma	Let feeding buffers dictate noncritical activities' start times.
Resource constraints occur across multiple projects	Recognize the resource(s) that is the critical chain
Multitasking happens	Avoid multitasking
Managers focus on cost	Focus on time
Projects finish late	All of the above

Safety time is embedded in individual tasks. There is evidence of inflated task-time estimates in practice. One example is weather-related padding used in construction (e.g., see Sears et al. 2008). In addition, there is evidence that pooling safety time is effective. For instance, Yeo and Ning (2006) present survey data and a model that suggest that pooled safety buffers are appropriate in construction equipment procurement supply chains.

However, in practice is it always the case that we should shift safety margins from task owners to pooled buffers? First, let's be clear what this means in CCPM.

Goldratt (1997) proposed a method sometimes called the *50% rule*, where original task-time estimates, and thus the critical chain's duration, are cut in half, and half of that savings is allocated to an end-of-project buffer. The net result? The planned project duration is 25% less time than the sum of original estimates. Feeding buffers are inserted where noncritical sequences join the critical chain using a similar procedure.

These methods drew some criticism. For example, Raz et al. (2003) argue that any benefits of pooled buffers have yet to be empirically justified and that "Imposing shortened duration estimates on task owners will reduce their commitment to the estimates. In addition, the knowledge that their estimates will be reduced is likely to encourage task owners to add larger margins so they still have the safety margin they prefer after the correction" (p. 27). Others have argued that this is not the case, that CCPM motivates a common goal. One illustration is the CCPM control of ITT's Night Vision project (Cook 1998, Jacob 1998). Raz et al. (2003) also worry that because each added buffer is a new item on a Gantt chart, this may result in more clutter, potential confusion, and possibly more unscheduled communication to coordinate the project team.

Others support the notion of pooled buffers. In fact, in the project management literature, the idea of a feeding buffer can be traced back to the 1980s (see Trietsch 2005, for references). That said, there is debate about their sizing rules. For example, Hoel and Taylor (1999) suggest buffer-size alternatives that give particular probabilities of on-time project deliveries.

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Others have said, "The ex ante realistic 50% task duration estimate may well be based on loose ground.... In many cases, the result might be an unnecessarily large amount of protection, which could lead to uncompetitive proposals and the loss of business opportunities" (Herroelen and Leus 2001, pp. 562–564). Specifically, one numerical experiment showed that the root-square-error method for buffer-size estimation is a more accurate approach (Herroelen and Leus 2001).

Having the most accurate buffer size and corresponding estimated completion date is of particular importance when projects must be won through bids that are evaluated, at least partially, based on the delivery date of the project. Indeed, almost every project selection method uses time in evaluating projects. For example, capital budgeting techniques use an interest rate to trade off time and money (Eschenbach and Cohen 2006), and the payback period is itself a time-based metric. Even methods that do not mandate explicit use of time estimates, such as cost/benefit analysis and scoring models, can readily account for time in their analysis. Also, when estimates are used for bidding purposes, best-value bids are not taken purely on cost, but on several factors, including delivery dates (Gransberg and Ellicott 1997, Kashiwagi and Byfield 2002). Hence, though an arbitrary 25% reduction in project duration may be impressive when the project manager and owner are the same, it may prove uncompetitive when projects must be won through bidding.

We know of several CCPM practitioners who do not use the 50% rule yet articulate the value of buffers. For example, Newbold (2009) says,

> [I]f you cut people's task durations by 50% as a standard approach, you run a huge risk of destroying the credibility of your schedules. More generally, poor schedule building or buffer sizing in any form can make buffering ineffective. However, the validity of the buffering concept is easily demonstrated and should be considered independently of the mechanism used to size buffers.

The message we emphasize with students is what other leading project management consultants told us: that more important than the question of the size of the buffer is the underlying cause of inflated task times, namely, that workers are held accountable for intermediate milestones even though such deadlines are irrelevant when projects finish on time. Thus, to get more accurate time estimates, two things are done: (a) the highest levels of management acknowledge in writing that individuals will not be held accountable for individual task deadlines, and then (b) particular language is used to coach employees to give good time estimates, such as, "what is your actual touch time on this activity?"

Step (a) is a rather dramatic cultural change for some firms. A recent case study of its effectiveness is the Japanese Ministry of Land, Infrastructure, Transport and Tourism, which created a culture of accurate time estimates and pooled safety time in public works projects. With the aid of several influential people including Kishira (2009a), and the related "Safety Bug" animated video series (Kishira 2009c), this so-called "Win-Win-Win Public Work Reform" has realized impressive lead-time reductions. Kishira's work highlights the two foregoing steps (a) and (b) that are necessary for buffering to work. As an aside, we find that Kishira's (2009c) videos liven any classroom discussion.

Parkinson's Law reigns. Parkinson (1955, p. 635) said, "Work expands so as to fill the time available for its completion," a phenomenon that was tested empirically (Moss 1978) and later confirmed in projects (Schonberger 1981, Gutierrez and Kouvelis 1991). Advocates of CCPM introduced the metaphor *student syndrome* (e.g., see Goldratt 1997, Budd and Cerveny 2010) to demonstrate their belief that Parkinson's Law leads to further delays.

Parkinson's Law has been well documented empirically. For example, Hill et al. (2000) found that 32% of 500 software development activities overran time estimates under traditional project control methods. This suggests that two-thirds of the activities were buffered to complete early or on time, an unlikely target at best. However, when one considers that Parkinson's Law resulted in time expanding to move average time closer to the buffered time, it is not surprising that only 68% of activities would be covered by a buffer chosen to achieve 90%–99% on-time completion.

Herroelen and Leus (2001) suggest Parkinson's Law is not necessarily bad, "since you cannot have the workforce under stress all the time" (p. 562). This raises the question of whether the student syndrome is the result of procrastination, as the name implies. Although there is a deep psychology literature that suggests that a complex array of factors contribute to procrastination (e.g., see Steel 2007), Bender et al. (2008) say, "The advantages of procrastination are well documented: the closer to a deadline a task is executed, the less processing time the task appears to require. Hence, it is common for a person to delay executing some onerous job in order to spend as little time as possible working on it" (p. 95).

Procrastination is not necessarily the result of laziness, but rather the case of workers with multiple deadlines on multiple projects. The expedient action (from the worker's point of view) is to optimize personal workflow by selecting tasks in order of individual deadlines. The message we emphasize to students is that, given a due date, it is rational (and likely efficient) to finish a job near the due date, and in reality,

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people do not estimate the time required to complete a task, but rather the time by which the task will be completed. That is, they quote due dates, not activity durations. Thinking of the estimate of an activity's duration as a due date, it no longer implies that someone is lazy or wasting time if they complete the activity near the due date. Rather, they are likely being efficient.

Regarding Parkinson's Law, it is worth noting that most people will not be assigned to just one task, but multiple tasks, perhaps on multiple projects. If they schedule their time efficiently, they will complete most of their activities on time, but not early. Again, this is not because workers are lazy or wasteful, but due to the structure of an optimal schedule for minimizing tardiness-based objectives. Whether or not CCPM reduces or outright avoids the impact of Parkinson's Law is still an open research question.

The importance of parallel activities is underappreciated. One of CCPM's motivations is that delays in noncritical activities can lead to unrecoverable project delays. On one hand, this assertion is well founded. For example, Schonberger (1981) showed that projects with variable activity times will always exceed the time of the deterministic critical path, with the greater the variability or number of parallel paths, the greater the delay.

The CCPM response is the insertion of feeding buffers where noncritical sequences join the critical chain. However, the more parallel paths in a project, the greater the chance that noncritical chains will turn critical, and thus feeding buffers will have been misplaced (Raz et al. 2003). Whereas some CCPM practitioners argue for careful daily monitoring of buffer consumption (see, for example, Gupta 2008, 2010), our example in §4.3b is designed to bring student attention to this point; note how all feeding buffers cannot be assigned a time duration prescribed by the 50% rule.

There is an early versus late start dilemma. If noncritical activities follow earliest or latest start times, it is said that the project leader will lose focus, resulting in costly delays (e.g., see Goldratt 1997). The remedy according to CCPM is that feeding buffers dictate the start of noncritical sequences.

One criticism of the approach, according to Herroelen and Leus (2001, pp. 565–566) is that

> Pushing activities backward in time in order to insert a feeding buffer may, and mostly will, create resource conflicts. How these conflicts are to be resolved is not described in detail. A possible way for resolving the conflict may be to push the chain of activities feeding a feeding buffer backwards in time until a feasible schedule is obtained again.

The example in §4.3 is designed to highlight other feeding buffer insertion complications.

Resource constraints occur across multiple projects. Although not new, resource leveling through the critical chain—that is, keeping the amount of resources tied up in a project as consistent as possible over the project's lifetime—is an important element of CCPM. However, Raz et al. (2003) question the applicability of a critical chain project solution given that the binding resource across different projects could alternate at different points of time. We invite students to explore a simpler case of constraints across projects using the example in §4.4.

Multitasking happens. It is our experience teaching CCPM to undergraduates that an important lesson is the loss of focus and productivity and increase in lead times induced by what CCPM practitioners call "multitasking" (Goldratt 1997) or "multi-tasking" (Budd and Cerveny 2010). Undergraduates often remark how they identified and eliminated multitasking in their personal lives as a result of the reading. By multitasking, we mean the assignment of one resource to multiple tasks or projects, potentially leading to task completion delays, and thus possible project delays. However, because of the more familiar meaning of multitasking in North American culture—"the human attempt to do simultaneously as many things as possible, as quickly as possible, preferably marshalling the power of as many technologies as possible" (Rosen 2008, p. 105)—students sometimes miss this point. To clarify this difference, we recommend reviewing the (Goldratt 1997, p. 126) figure to explain the project definition.

This notion can be further demonstrated by having students play the multitasking game in class. Students roll dice to randomly simulate the progress made on three separate identical projects each week. First, students simulate project execution with multitasking when each project is given equal priority and workers alternate between projects. Second, students simulate project execution without multitasking when projects are prioritized and workers concentrate on the highest-priority project. One of the authors has had success using this game to demonstrate multitasking in the classroom, and the game has also seen successful use in project management courses at Case Western Reserve University (Vairaktarakis 2010) and Ohio State University (Hall 2010). A simple online multitasking activity is also available to demonstrate the concept for projects (http://billiondollarsolution.com/multitasking.html).

To contrast the cultural definition, we invite students to listen to Hamilton (2008) and the humorous Sharp (2008), as well as to play the online game "Multitask" (http://www.kongregate.com/games/IcyLime/multitask).

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With regard to the cultural meaning of multitasking, the research firm Basex estimated that interruptions and information overload of white-collar/knowledge-based workers take a $650-billion toll on lost productivity and innovation throughout the U.S. economy (Lohr 2008). However, assuming that interruptions are kept to a minimum, there is evidence that the project management definition of multitasking is beneficial when carefully applied to projects. For example, McCollum and Sherman (1991) found that assigning R&D employees to up to three simultaneous projects improved return on investment. Trietsch (2005) concurs that multitasking is unavoidable, and sometimes desirable, in practice. In addition, according to Demeulemeester and Herroelen (1996) and Hillier and Lieberman (2001), multitasking can lead to activity preemption, stopping work on a lower-priority activity to work on a higher-priority activity that has just become available, which has been shown to shorten project durations.

Indeed, it is well known that multitasking increases scheduling flexibility. In the end, there is a difference between efficient assignment of resources to a project and efficient use of resources within an organization. Also, there is a difference between departmental and individual commitments to complete a task. Departments obviously must accept many requests for work, so requiring that no one in a department be assigned to more than one task at a time would make the department manager's scheduling task impossible, even if it works for the project manager. In the end, properly used, multitasking should improve project success; abuse of multitasking can prove detrimental to a project's success.

Managers focus on cost. Evidence suggests that a "cost-minimization mentality" is less profitable. For example, Port et al. (1990) cite a McKinsey & Co. estimate that firms lose one-third of their profits when they accept six-month delays to stay within product development budgets; spending 50% more than budgeted to meet a release date attenuates total profits only 4%.

Of course, this is dependent on the definition of "on time." If buffers and due dates change, then the meaning of "on time" also changes. If PERT/CPM project management is about completing projects on time with minimum cost and if the notion of on time is erroneous, this can be a failed approach. However, net present value (NPV) project management is geared toward maximizing project NPV (Herroelen et al. 1997) and can clearly identify what on time should mean. Hence, although practicing project managers may tend to focus too much on cost and not enough on time, this is not a deficiency in project management theory itself, which seeks to balance the objectives of time and cost. Indeed, always striving to complete earlier with no regard to budgets can be just as detrimental to project success as sacrificing time for cost. In particular, when the project manager's company is acting as a contractor and does not own the completed project, the benefits of earlier project completion are significantly less. Further, these benefits may well be clearly quantifiable based on the contract with the project owner.

Overall, it is a valid point that project success is not about meeting a target project budget or even a target project due date. If the goal of a project is to generate profit, then the ultimate profitability of the project could be the determinant of the project's success. If profitability can be improved by spending more money to finish sooner or by spending less money to finish later, then so be it.

Finally, we suspect that the focus on time, not cost, is the spirit of W. Edwards Deming's fourth point: "end the practice of awarding business on [the] price." (Deming 1986, p. 23).

Projects finish late. The characters in Goldratt (1997, p. 25) joke that, "Everybody knows projects don't finish on time or on budget, and even if they do, it means they had to compromise on content." Frequently cited empirical evidence of this statement is the Standish Group's long-term study of thousands of IT projects around the globe. The average delay, cost overrun, and percent canceled prior to completion are noteworthy (for details, see Woeppel 2005, Klastorin and Mitchell 2005). Leach (2005) surveys other project management planning anecdotes in other industries. The question, however, is this: is CCPM the antidote to late projects? We address this in more detail in the next section.

3. Does CCPM Deliver?

We are unaware of any scientific study that assesses performance metrics of a sample of projects controlled with CCPM versus traditional methods. That said, the number of case studies of successful project execution due to CCPM is burgeoning. These include private, public, and government agencies, and the documented improvements include substantial time savings, profitability, customer satisfaction, and worker enthusiasm. Table 3 gives a sample from Cook (1998), Barber et al. (1999), Cabanis-Brewin (1999), Leach (1999), Simpson and Lynch (1999), Umble and Umble (2000), Parr (2000a), Rand (2000), Fenbert and Fleener (2002), Gupta (2003), Hunt (2004), Srinivasan et al. (2004), Leach (2005), Woeppel (2005), Srinivasan et al. (2007), Goldratt (2009), Kishira (2009b), Jensen (2010), and the testimonials from Realization Technologies, Inc. (see http://www.realization.com) and Avraham Goldratt Institute (AGI; see http://goldratt.com).

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Table 3 Organizations That Documented Project Management Improvements Due to CCPM

A13 Motorway Construction Project (United Kingdom)	Japanese Ministry of Labor, Infrastructure, Transport & Tourism (MILT)
Abb Group	LeTourneau, Inc.
Action Park Multiforma Grupo	Lockheed Martin
Airgo Networks (now QualComm)	Lord Corp.
Alcan Alesa Technologies	LSI Corp.
Alna Software	Lucent Technologies (now Alcatel-Lucent)
Amdocs	Marketing Architects, Inc.
Balfour Beatty Civil Engineering Ltd.	Medtronic
BHP Billiton	Northern Digital, Inc.
Boeing, Space & Intelligence Systems, Manufacturing R&D and Satellite Manufacturing, and F22 Raptor	Oregon Freeze Dry, Inc.
Bosch Security Systems	Pratt & Whiney
Central Nuclear Almaraz Trillo	Proctor & Gamble Pharmaceuticals
DaimlerChrysler, Automotive Product Development	Rapid Solutions Group
Delta Airlines	Skye Group
Dr. Reddy's Laboratories	Tata Steel
Duke Energy	TECNOBIT
e2v Semiconductors	Thru-Put Technologies
Eircom	ThyssenKrupp Krause, Ltd.
Erikson Air-crane	U.S. Army: Corpus Christi Army Depot
French Air Force	U.S. Air Force: Operational Test & Evaluation Center, Warner Robins Air Logistics Center (ALC), Ogden ALC, Oklahoma City ALC
Genencor	U.S. Marine Corps: Logistics Bases in Albany, GA & Barstow, CA
Habitat for Humanity	U.S. Navy: Cherry Point, NC Aviation Depot, Pearl Harbor Shipyard
Hamilton Beach/Proctor-Silex, Inc.	Valley Cabinet Works
Harris Semiconductor	Von Ardenne
Hewlett-Packard, Digital Camera Group	Votorantim
Honeywell Defense Avionics Systems	
Israeli Aircraft Industry	
ITT Corporation	

Although some of the above references were not peer reviewed or were contributed by authors with an economic interest in the CCPM methodology, we suspect the actual list of successes is longer. For example, by 1999 it was said that CCPM was proved in more than 1,000 case studies (Cabanis-Brewin 1999), and we know of several consultants bound by nondisclosure agreements who talk off the record about impressive achievements due to CCPM in well-known corporations and government agencies.

The gains due to CCPM within the Japanese Ministry of Land, Infrastructure, and Transportation are worth highlighting. To our knowledge, it is the largest wholesale adoption of CCPM in any organization. According to the Afinitus Group (2008),

> A single successful pilot project on Hokkaido in 2005 led to 15 more successful Hokkaido pilots in 2006. In 2007, based on the impressive results of the pilot projects, CCPM began to be rolled out voluntarily across Japan, with 2,523 projects using the TOC approach. In 2008 the number rose to over 4,000 projects, leading to the government announcement that CCPM should be used on all projects henceforth (approx. 20,000 projects per year).

In the interest of a balanced appraisal of CCPM, one might ask if reported gains are attributable to the Hawthorne Effect (changes in behavior due to being studied) or the novelty of new management methodologies. The literature is inconclusive, although some argue informally that the Hawthorne effect is unlikely in project organizations (e.g., see Cabanis-Brewin 1999, pp. 50–51). Two related concerns are noteworthy: sustainment—the endurance of CCPM control methods after the original "CCPM champion" has been promoted or otherwise moved on—and outright project failures. We know several cases in industry and the U.S. military where these have been problematic but not reported publically.

Another pair of related issues is self-selection and self-reporting of users of CCPM. With regard to self-selection it may be the case that only those users for whom non-CCPM tools are failing would try CCPM. Hence, the case-by-case comparison of CCPM and non-CCPM practices is biased against non-CCPM tools. With regard to self-reporting, it seems likely that companies are more likely to promote and publicize successes than project failure stories. Hence, a number of failed CCPM attempts are likely to go unreported. Indeed, our conversations with consultants reveal that such events are likely to be shielded by nondisclosure agreements.

Finally, scholars have written about situations in which CCPM is theoretically not the ideal control method. For example, Herroelen and Leus (2001) suggest buffer-sizing improvements in single- and multiple-project environments, and similarly, Cohen et al. (2004) suggest alternatives to CCPM control that reduce makespans of multiple projects.

4. Numerical Examples and Counterexamples

We now present a sequence of numerical examples to motivate critical thinking and provide supplemental practice in critical chain scheduling. A teaching note with detailed solutions is available to qualified instructors from http://ite.pubs.informs.org/.

4.1. Simple CCPM Formulation: The Project of Jack and Jill

The first example is a simple resource-constrained project that we find useful for less technical undergraduate students from various business disciplines. Some will find this example unnecessary; it was conceived for the student who does not immediately understand the meaning of person "X" in the (Goldratt 1997, p. 218) figure. Consider a project with

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the activity precedence relationships and time estimates given in the following table.

Activity	Immediate predecessor	Estimated time (weeks)
A	—	6
B	A	12
C	A	4
D	B, C	10

Two workers are available. Because of her skill set, Jill is responsible for activities A and D. Similarly, only Jack can do activities B and C.

(a) Assuming that the time estimates are perfectly accurate, what is the planned project duration? Explain. (Use the time estimates as is; do not insert project or feeding buffers.)

(b) Which activities are critical? Explain.

(c) Assume Jack and Jill can be cross-trained to do any activity, but will not share activities. Can the activities be reassigned to Jack and Jill such that the project is completed in less time? If so, indicate the new assignment and project duration.

(d) Consider the following staffing assignment: Jill does activities A and B, Jack does activities C and D. Assume that the times in the foregoing table are estimates padded with safety time. Use critical chain scheduling ideas to reformulate the project schedule using project and feeding buffers. Include a diagram similar to that in Goldratt's (1997, p. 218).

4.2. Resource Constraints Within a Project: The Project of Person "X"

This example was also developed to aid in debriefing (Goldratt 1997, pp. 214 and 218), specifically the conceptual project diagrams. The following example asks students to develop such a diagram from a numerical example.

Consider the following project activity list.

Activity	Immediate predecessors	Estimated activity time (weeks)
A	—	5
B	A	4
C	—	3
D	C	9
E	—	2
F	E	5
G	F	3
H	G	8
I	B, D, H, K, M	4
J	—	3
K	J	2
L	—	1
M	L	7

One person (called person "X") is the only employee with the skills needed to accomplish activities B, D, F, K, M. Each remaining activity (A, C, E, G, H, I, J, L) has a unique person assigned to the task and can therefore be completed independently of other activities. Develop a critical chain project schedule. Include a figure similar to that on page 218 and indicate the duration of activities and buffers.

4.3. PERT vs. CCPM: The Project of Reliable Construction Company

The purpose of this next example is to convert a well-known PERT problem into a critical chain plan using CCPM methods, forcing students to consider methodological differences between PERT and CCPM. It also presents three situations not formally addressed in most CCPM references: (i) when critical activities precede noncritical activities, (ii) when there is task-time distribution information, and (iii) when the 50% rule for feeding buffer allocation is infeasible. Again, because we introduce the method from Goldratt (1997), the problem is framed in terms of that reference, although it need not be.

Consider the project of Reliable Construction Co. (Hillier and Lieberman 2001) with the precedence relationships (Table 10.1, p. 469) and optimistic (o), most likely (m), and pessimistic (p) time estimates (Table 10.4, p. 488) and expected critical activities A–B–C–E–F–J–L–N that yield the expected project duration 44 weeks.

(a) In Goldratt (1997, p. 156), the characters ultimately decide that "time allotted for each step will only be cut by one-half. On the other end, the project buffer will not be equal to what they trimmed. It will be set to only half of it." We call this the 50% rule. Considering the spirit of the 50% rule, reformulate each time estimate and the duration of the project buffer. What is the revised planned project duration?

(b) Similarly, regarding noncritical activities, "For each feeding path they decide to cut the original time estimates of the steps in half and use half of the trimmed lead time as a 'feeding buffer'" (Goldratt 1997, p. 158). Use this information to sketch a figure similar to that at the bottom of page 158 for the project. In the figure, indicate the duration of each activity and buffer.

(c) The 50% rule is just one approach to achieve a more general philosophy of CCPM, namely, that activity times should not be padded but rather "aggressive but doable" with collectively shared buffers inserted in appropriate places (i.e., the project and feeding buffers). However, when you considered a PERT problem, you were presented with three numbers: optimistic, most likely, and pessimistic time estimates for each task. Describe how you used these three times to create an "aggressive but doable" estimate for each task and your reasoning for doing so. Explain.

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Table 4 Current Project Management Software Tools with Critical Chain Capabilities

Tool	Company	Year	Website
Agile-CC for AdeptTracker	WangTuo Software	2008	http://www.adepttracker.com/index.html
Aurora-CCPM	StottlerHenke Associates, Inc.	2011	http://www.stottlerhenke.com/product/products/aurora-ccpm/
BeingManagement CCPM	Being Co. Ltd.	2011	http://www.toc-ccpm.net/eng/index.html
cc-Pulse/cc-MPulse	Spherical Angle	2011	
CCPM+	Advanced Projects, Inc.	2011	http://www.advanced-projects.com/home.aspx
Concerto	Realization Technologies, Inc.	2011	http://www.realization.com
Lynx	A-Dato Scheduling Technology	2011	http://www.a-dato.net
ProChain	ProChain Solutions, Inc.	2011	http://www.prochain.co
PSNext	Sciforma Corp.	2011	http://www.sciforma.com

4.4. Resource Constraints Across Multiple Projects: The Company of Jack & Jill & Jane

The purpose of this problem is to give students practice with resource constraints across projects, an idea that is mentioned but not developed in the references in Table 1.

The company of J&J&J has two projects. One is the project of Jack & Jill (where Jill must perform A and D and Jack must perform B and C, as given in the table in §4.1). The other is the project of Jack & Jane, which is identical to the project of Jack & Jill, but the activities are labeled E, F, G, and H where Jill must perform E and H. It is more expensive to delay the project of Jack & Jill. Find a good schedule for these two projects.

4.5. Anecdotal Reasoning?

CCPM supposes that task buffering is wasteful in organizations and that it is easy to eliminate vast amounts of time from a project. For example, in (Goldratt 1997, pp. 183–184), the hero manages to get a coatings subcontractor to agree to "drop everything else and work on it" when a job arrives. The only apparent barriers for the subcontractor are a price increase and that he be given 10 days notice (with updates) of the job's arrival. Identify as many problems with this exchange that you can imagine. Explain.

4.6. CCPM Software; Other Computer Activities and Games

According to Vinson (2010), there are several project management software tools with critical chain capabilities (see Tabel 4). ProChain is available to professors at no charge (see http://www.prochain.com/services/university-program.html). Instructors of more-advanced project management classes may wish to ask students to formulate the examples in §§4.1 to 4.4 using such software.

In addition to the multitasking games mentioned earlier, other CCPM games worth considering include Holt's (2011) and what is now being called "Tony Rizzo's Bead Game" for resource-constrained project scheduling in a multiproject setting (see Roggenkamp et al. 2005). Also see the CCPM exercises in Doyle (2010).

5. Conclusion

We hope that this document gives instructors actionable ideas for their project management lesson plans and helps them decide what content regarding CCPM, if any, they will include in a syllabus. Our conclusion is that a unit on CCPM enriches a traditional project management course by exposing the potential pitfalls of standard scheduling methods. Whereas some practitioners tell us that CCPM replaces such methods, from a pedagogical perspective we feel CCPM is a complement. It is the comparing and contrasting of CCPM with established practices that motivates deep student thinking and learning.

Despite the lack of scientific, peer-reviewed evidence about the effectiveness of critical chain project control, we feel the method contributes unique enrichment to a student's project management education. In the way Deming's methods were about instilling cooperation in teams to work toward a common goal, the teachings of CCPM promote more selfless collaboration in project organizations. For example, the majority of the success stories surveyed in Table 3 include anecdotes of renewed worker enthusiasm, enhanced sense of teamwork, and more joy in work. On this basis, it seems that the cultural shift of eliminating individual milestone responsibilities and the resulting coordinated teamwork under aggressive time estimates and shared buffers have the potential to be one of the most important contributions and innovations due to the methodology.

Finally, CCPM was never intended to address certain aspects of project management that are thus intentionally absent from this review. These include the distinction between successful projects and successful project planning (for more, see Raz et al. 2003), capital budgeting and the strategic importance of choosing the right projects, and budgeting individual projects properly. We also do not address how one teaches CCPM implementation nor how CCPM methods accommodate scope creep.

Supplementary Material

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