Chapter 3
The Critical Path Method

Abstract This chapter makes an effort to tighten the gap between the project scheduling literature and the needs of project managers and schedulers through the use of a practical computerized simulation game. Project managers are constantly confronted with the intricacy of scheduling a complex real-life problem in an efficient way when they often have little knowledge of the state-of-the-art in the algorithmic developments or inherent characteristics of the scheduling problem they solve. A game has been developed that serves as a training tool to help practitioners gain insight in project scheduling. The well-known critical path method (CPM) with activity time/cost trade-offs is introduced to the reader, and used as a project scheduling technique in the game.

3.1 Introduction to Literature

Project scheduling has been a research topic for many decades, leading to a project management body of knowledge containing a wide and diverse set of principles, tools and techniques. In recent years, several summary papers have given an overview of the past and current development in project scheduling literature (see, for example, the papers by Icmeli et al. (1993), Elmaghraby (1995), Özdamar and Ulusoy (1995), Herroelen et al. (1998) and Brucker et al. (1999)). These papers primarily focus on the modeling aspect and algorithmic developments necessary to schedule complex projects and parts of them will be discussed in later chapters of this book. A more recent experimental investigation of heuristic search methods to construct a project schedule with resources can be found in Kolisch and Hartmann (2006).

The wide diversity of project scheduling topics and research projects is reflected in two classification schemes developed by Brucker et al. (1999) and Herroelen et al. (1999). In these papers, the authors summarize and classify the main features and characteristics of various kinds of project scheduling problems according to project features, resource characteristics and scheduling objectives. Despite this ever

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growing amount of research on project scheduling, it has been shown in literature that there is a wide gap between the project management discipline and the research on project management, as illustrated by Delisle and Olson (2004), among many others.

This chapter makes an effort to tighten the gap between the project scheduling literature and the needs of project managers. Project managers are constantly confronted with the intricacy of scheduling a complex real-life problem in an efficient way when they often have little knowledge of the state-of-the-art in algorithmic developments. A Project Schedule Game (PSG) has been developed that serves as a training tool to help practitioners gain insight in project scheduling. The game is based on data from a real-life project from a water production center as an input (details about the real project are given in Chap. 4) but allows the incorporation of any project suggested by the participants. The purpose of the game is to get familiar with the well-known *discrete time/cost trade-off scheduling problem* as an inherent characteristic of the *Critical Path Method* (CPM), which will be discussed in detail throughout this chapter. The game helps to show the project manager how to cope with trade-offs between activity durations and their corresponding costs and creates an incentive to rely on academic research efforts and/or algorithmic procedures developed by many researchers in the field. The problem discussed in the current chapter can – similar to the previous chapter – be classified in quadrant 1 of Fig. 1.4.

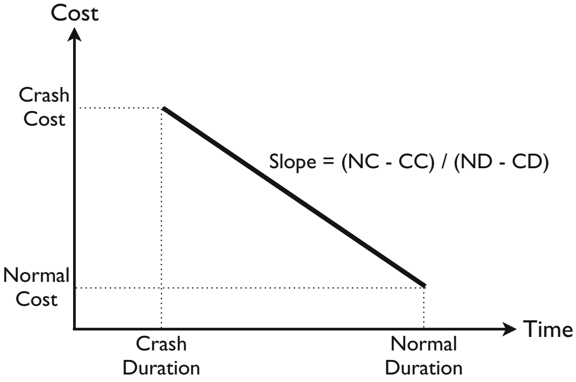
The outline of this chapter is as follows. Section 3.2 gives an introduction to the Critical Path Method (CPM). Section 3.3 gives an overview of the features of the game. It discusses why managers can benefit from a project scheduling game and gives a short presentation of the real-life example project used in the PSG. Section 3.4 discusses the educational approach taken during a typical PSG class session. Section 3.5 draws overall conclusions.

3.2 Time/Cost Scheduling Trade-Offs

3.2.1 Linear Time/Cost Relations

Time/cost trade-offs in project scheduling find their roots in the Critical Path Method, developed between 1956 and 1959 at the Du Pont Company and at Remington Rand Univac (Kelley and Walker 1959; Walker and Sawyer 1959; Kelley 1961), which is originally based on an activity-on-the-arc network diagram. Since then, a never-ending amount of literature has focused on the extensions of this basic problem type. Basically, CPM assumes that the duration of project activities is a nonincreasing function of the amount of money used to perform this activity (i.e. money is considered here as a single nonrenewable resource; for more information on resources, see Chap. 7). This implies that the cost of an individual activity is a function of its duration, that is, by spending more (or less) nonrenewable

Fig. 3.1 The time/cost trade-off of an activity



resources (money), the activity duration will decrease (or increase). Note that this chapter belongs to Part I of this book, where no resources are explicitly taken into account. In Chap. 7, a distinction will be made between renewable resources and nonrenewable (or consumable) resources and it will be shown that the presence of renewable resources (and *not* the presence of the nonrenewable resources that will be used in the current chapter) leads to an increase of the scheduling complexity. Consequently, the use of nonrenewable resources to incorporate a time/cost trade-off in project activities does not lead to a significant increase in the project scheduling complexity compared to the techniques of the previous chapter, which is exactly the reason why the CPM is discussed in this part of the book.[1]

A CPM project scheduling model assumes four pieces of information for each project activity, as follows:

- Normal Duration (ND): The maximum duration for the activity.
- Crash Duration (CD): The minimum duration for the activity.
- Normal Cost (NC): The cost associated with the normal duration.
- Crash Cost (CC): The cost associated with the crash duration.

The early time/cost trade-off models assumed the direct activity cost functions to be linear nonincreasing functions, as shown in Fig. 3.1. The objective was to determine the activity durations and to schedule the activities in order to minimize the project costs (i.e. the sum of the activity costs) within a specified project deadline. Therefore, the activity costs are a function of the activity durations, which are bounded from below (crash duration) and from above (normal duration). Consequently, the project manager needs to decide the optimal timing for each activity by selecting a time/cost combination for each activity. To that purpose, each

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[1] Note that this classification can be subject to discussion. The discrete time/cost trade-off problem as discussed in Sect. 3.2.2 is known to be NP-hard, and hence, constructing an optimal schedule for this scheduling problem is known to be a very difficult problem. However, due to the absence of renewable resources, the problem is considered as easy (quadrant 1 of Fig. 1.4) relative to the resource-constrained projects of quadrant 3. Details are outside the scope of this book.

activity duration can be reduced to less than its normal duration, which is known as *activity crashing*. The slope of the time/cost curve determines the marginal crash cost per unit of time as follows:

$$\text{Unit Crash Cost} = \frac{\text{Normal Cost} - \text{Crash Cost}}{\text{Normal Duration} - \text{Crash Duration}}$$

Originally, the CPM has been modeled in an AoA network representation. Figure 3.2 shows an example AoA project network with five nondummy activities with each activity labeled with (CD, ND, UCC), with CD the crash duration, ND the normal duration and UCC the unit crash cost for each activity represented by arc (i, j).

The time/cost trade-off scheduling problem can be formulated by the following linear programming model (Elmaghraby 1977):

$$\text{Minimize} \sum_{(i,j)\in E} c_{ij} y_{ij} \tag{3.1}$$

subject to

$$t_i - t_j + y_{ij} \leq 0 \qquad \forall (i, j) \in E \tag{3.2}$$

$$cd_{ij} \leq y_{ij} \leq nd_{ij} \qquad \forall (i, j) \in E \tag{3.3}$$

$$-t_1 + t_n = \delta_n \tag{3.4}$$

The variable t_i is used to denote the realization time of event (node) i and the variable y_{ij} to denote the duration of activity (i, j). The parameter c_{ij} is used to represent the marginal cost of crashing activity i with one time unit (i.e. the slope of the activity time/cost line as calculated earlier by the Unit Crash Cost). The parameters cd_{ij} and nd_{ij} are used to denote the crash and normal duration of activity (i, j). The set E is used to refer to the set of project activities in an AoA format, represented by the edges in the network. Note that the model assumes that the cost of completing the project on normal time is already determined. The objective of the formulation minimizes the extra cost of crashing activities to durations lower than their normal duration. The cost of crashing is assumed to be a linear function of the activity duration varying between the crash and normal duration. The t_i variables

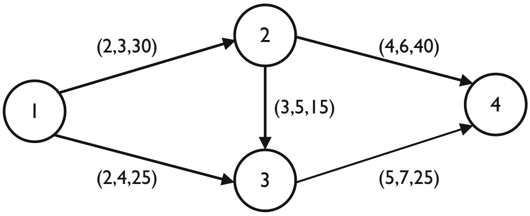

Fig. 3.2 A fictitious AoA network with five nondummy activities

are not restricted in sign, as shown by Elmaghraby (1977). Details are outside the scope of this book.

The optimal crashing cost for the example project of Fig. 3.2 with a predefined deadline of $\delta_n = 12$ is equal to 55. The activity durations are equal to 3, 4, 3, 6 and 6 for activities (1,2), (1,3), (2,3), (2,4) and (3,4).

Due to its inherent complexity and relevance in practice, numerous solution procedures for this CPM scheduling problem are proposed for other than linear activity cost functions, including concave, convex and general continuous activity cost functions. In the next section, a practical extension to discrete time/cost relations is discussed, which will be used in the PSG. Furthermore, in the remainder of this chapter, project networks will be represented by the AoN format instead of the AoA format.

3.2.2 *Discrete Time/Cost Relations*

A lot of procedures have also been developed for solving the discrete version of the scheduling problem in which the duration of project activities is a discrete, nonincreasing function of the amount of a single, nonrenewable resource committed to them. Figure 3.3 shows an example of a discrete activity time/cost profile containing five possible (time,cost) combinations. Each combination is referred to as an *activity mode* and the scheduling problem involves the selection of a set of execution modes for all project activities in order to achieve a certain objective. The problem has been studied under three possible schedule objectives, as follows:

- Deadline restriction: This CPM type involves the scheduling of all project activities in order to minimize the total cost of the project while meeting a given deadline.
- Budget restriction: This CPM version aims at minimizing the project duration without exceeding a given budget.

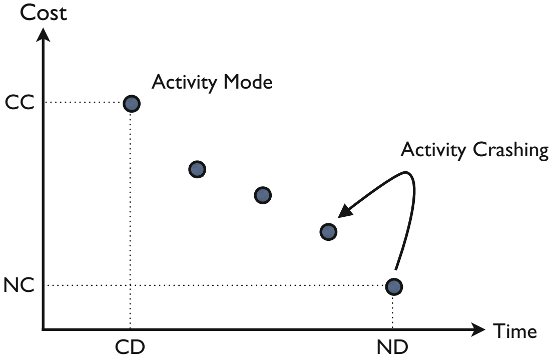

Fig. 3.3 A discrete time/cost trade-off for an activity

- Complete horizon: This CPM version combines the two previous ones and involves the generation of an efficient time/cost profile over the set of feasible project durations. That is, all the efficient points (T, C) so that, a project length T can be obtained with a cost limit C and, so that, no other point (T′, C′) exists for which both T′ and C′ are smaller than or equal to T and C.

Thanks to the relevance of this *discrete time/cost trade-off problem* (DTCTP) in practice, numerous researchers have investigated this problem. An Integer Programming (IP) formulation of the scheduling problem is outside the scope of this book. For more detailed information about problem formulations and solution methods, the reader is referred to papers written by Crowston and Thompson (1967), Crowston (1970), Robinson (1975), Billstein and Radermacher (1977), Wiest and Levy (1977), Hindelang and Muth (1979), Patterson (1979), Elmaghraby and Kamburowsky (1992), De et al. (1995, 1997), Demeulemeester and Herroelen (1996), Demeulemeester et al. (1998), and Skutella (1998). In the next sections, the DTCTP will be embedded in the simulation game, such that project managers can easily get acquainted with the scheduling problem, without knowing exact formulations or advanced solution methods.

3.3 The Project Scheduling Game

The *Project Scheduling Game* (PSG) is an IT-supported simulation game that illustrates the characteristics of scheduling a real-life project with discrete time/cost trade-offs in the project activities. The project is based on a sequence of activities for a large real-life project at the Vlaamse Maatschappij voor Watervoorziening, which aims at the expansion of the capacity to produce purified water (the data are based on the project description of Chap. 4). As explained in the previous section, the participant (manager) of the game has to construct a dynamic project schedule for the discrete time/cost trade-off problem. Indeed, by allocating nonrenewable resources (money) to a particular activity, the manager decides about the duration and corresponding cost of each network activity. The manager schedules the project with the negotiated project deadline in mind, focusing on the minimization of the total project cost.

3.3.1 Why Do Managers Need This Game?

It has been mentioned in Chap. 1 that a project typically goes through a number of different phases, which are often referred to as the project life cycle. Such a life cycle might consist of a project conception phase, a project definition phase, a phase in which the project has to be scheduled, the execution of the project, the controlling phase in which the progress of the project is monitored and the final termination of

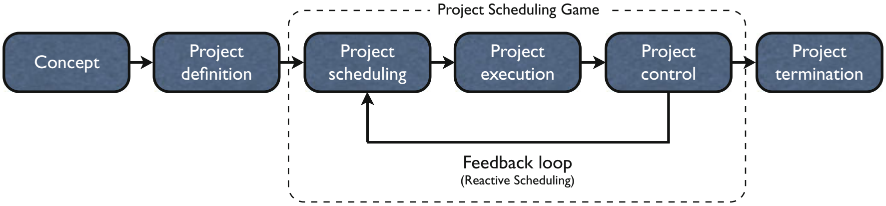

Fig. 3.4 The PSG project life cycle

the project. The project of the game, like any project, goes through these different phases. The conception and definition phases are assumed to be completed and serve as inputs to the simulation game. The project concept and the simulation process of the PSG are described in Sect. 3.3.3. The game simulates the scheduling, execution and control phases of the project, as shown in Fig. 3.4. Participants playing the game focus on the scheduling of the project (scheduling phase), receive feedback from the project control phase (feedback loop) and reschedule as the project is being executed. This approach is referred to as reactive scheduling (see Chap. 1).

The various algorithmic developments in literature dealing with the scheduling phase are strongly related with optimization modeling and require, therefore, the necessary skills and technical know-how (In literature, researchers often refer to the NP-hardness to denote the complexity of most scheduling problems (see, for example, Demeulemeester and Herroelen (2002)). Unfortunately, the manager who is in charge of the project often has little or no background in optimization and, consequently, unintentionally ignores the recent developments in the field. One of the major goals of this project scheduling game is to create a feeling of the inherent complexity of the project scheduling phase (even for projects in quadrant 1 of Fig. 1.4, which are labeled as rather easy, scheduling complexity issues arise) and to create an incentive to rely on the state-of-the-art developments by different universities. Indeed, research has revealed interesting insights in the crashing behavior of activity durations under different assumptions (linear, convex, concave, discrete or arbitrary time/cost trade-offs).

However, completely relying on algorithms to schedule real-life projects ignores the fact that uncertainty will occur. Indeed, due to unexpected events (a delay in an activity, a machine breakdown, a strike, an inaccurate estimate of resource usage, etc.) the execution of the project will differ from the original schedule. Periodically, the manager has to control the execution and adapt the preliminary schedule. A thorough understanding of the technical details and complexity of the scheduling mechanism is, therefore, indispensable. Consequently, the project manager has to update the project schedule of the game during the project's progress as new information arrives, and hence, considers the scheduling problem as a dynamic scheduling problem that needs modifications at regular time intervals. While the current approach has a clear focus on a *reactive scheduling* approach to deal with uncertainty, other approaches will try to analyze the risk during the construction of the schedule to shift to more *proactive scheduling* approaches (see e.g. Chap. 5). This proactive scheduling approach is not incorporated in the simulation game.

In the next section, the features of the real-life project used in the PSG business game are discussed. Note that the project characteristics discussed in the next section are a result of the project conception and definition and planning phase and are used as input for the manager (i.e., the player) who is now put in charge of scheduling the project.

3.3.2 The Project Data of PSG

The PSG requires project data consisting of a network with project activities and precedence relations, and multiple time/cost estimates for each activity. Moreover, project execution has to be simulated during the execution phase of the project, which requires input for uncertainty in the activity durations. Although this uncertainty aspect is unknown for those who play the game, it has to be defined by the game teacher in advance. While the software runs with any project that is correctly entered in the input screen of the game, a predefined project network is mostly used during the teaching sessions. The advantage of using predefined project data is twofold. On the one hand, it is less time consuming since entering time/cost data requires a tailoring step in order to be sure that the game reflects a realistic project setting. On the other hand, since both the project network and the uncertainty is known by the game developer, the optimal solution is known and available upon request, which can act as a validation tool that can be shown to the participants at the end of the game run (see Fig. 3.9 of Sect. 3.4).

The default project is based on project data obtained from the Vlaamse Maatschappij voor Watervoorziening (VMW), a Flemish water distribution company, which covers approximately 50% of Flanders, located in the northern region of Belgium. This company produces and delivers water by transforming surface water into drinkable water and distributing it to the customers. The VMW services 2.5 million customers with a pipeline network of 27,000 km and a yearly production of 140 billion liters of water.[2] The project aims at the expansion of the capacity to produce pure water and is the topic of Chap. 4.

In the definition phase, the organization defines the project objectives, the project specifications and requirements and the organization of the whole project. In doing so, the organization decides on how it is going to achieve these objectives. The VMW has decided to perform the project in two major steps. In a first step, it will focus on an extension of the storage capacity of treated water without expanding the production capacity of pure water. The latter is the subject of a second step that aims at an increase of the production capacity of pure water. For educational purposes, the game focuses only on a subpart of the whole original project.

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[2] Data based on figures obtained in 2003.

The game takes the definition phase as an input and assumes that the organization has knowledge about the estimates of the durations and costs of the activities, and the precedence relations among these activities. The project scheduling game begins after this point of the project life cycle, taking the detailed description of the project as an input. The next step is to schedule the project in order to present a timetable for the project activities, which is under the responsibility of the game player. As previously mentioned, the game focuses on the construction of a precedence feasible schedule and the adaptation of this schedule during the execution and controlling phase, which is inevitable due to uncertain events.

Figure 3.5 displays the activity-on-the-node (AoN) network for the project. The project consists of 44 activities (and a dummy start and dummy end node), which can be divided into two main subprojects: the construction activities at the plant itself and all the remaining construction activities outside the plant. The project is different from the description of the original project (see Chap. 4), since it combines a number of activities into one domed activity for which time/cost trade-offs have been defined. This data is important since the game relies on the time/cost trade-off problem in order to illustrate the complexity issues of scheduling a real-life project. It is assumed that the structure of the network will remain unchanged throughout the simulation. This might differ from normal practice in which networks are often

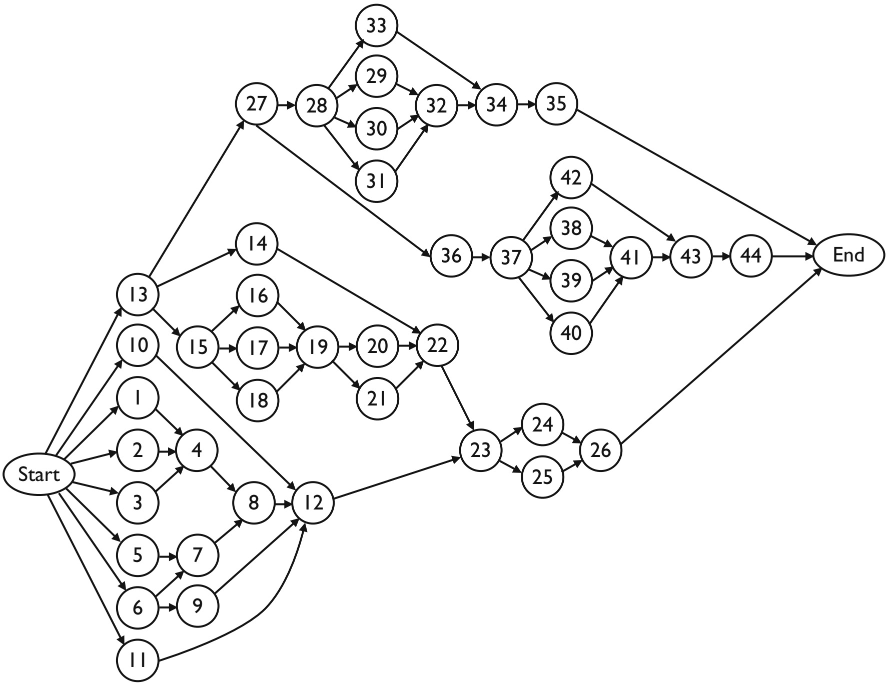

Fig. 3.5 The default PSG project network

changed substantially as the project progresses. A list of the project activities and their possible time/cost trade-offs is given at the end of this chapter in Table 3.1.[3]

In the next section, the project scheduling game is described in more detail, with a clear focus on the scheduling and controlling phases of the project life cycle.

3.3.3 Simulation Process of PSG

Each of the 44 individual activities shown in Fig. 3.5 must be finished to complete the capacity expansion project and this must be done in a sequence that does not violate the precedence relationships shown in the network diagram. As in real life, the activities that make up the total project do not have a single, fixed duration, but can vary with the amount of money that management spends (the so-called time/cost trade-off). The primary task for a project management team is to decide on the activity durations to be scheduled for each activity, taking into account costs and the project completion time. In addition, there are factors beyond control of management that can influence the length of an activity. During the project, occurrences such as strikes or acts of nature may cause some activities to be delayed beyond their planned duration. On the other hand, fortune may smile and result in an earlier-than-scheduled completion of some activities.

One of the unique features of the PSG is that it completely relies on the interaction between the scheduling, execution, and controlling phase (see Fig. 3.4) and makes use of the feedback loop in order to monitor the progress of a project. Indeed, during the execution phase the project has to be monitored and controlled. If deviations from the existing schedule occur, corrective actions have to be taken (previously referred to as reactive scheduling). Figure 3.6 displays the simulation process of the game indicating the inputs and outputs generated by the software and inputs needed by the user. In the following paragraphs, the various simulation steps of the figure are discussed in detail.

Start of the game: The game starts with an original schedule proposed by the game developer or the teacher entering new project data in which scheduled activity duration decisions have already been made. This results in an expected completion time T for the project, as well as a total cost for completing the project. The expected completion time is obtained by adding up the total time to complete the activities along the critical path in the network (as previously mentioned, the time/cost trade-off finds its roots in the critical path method). It is assumed that all weekends and holidays are also working days.[4] Total project cost is made up of the sum of the penalty cost (described below) and the planned activity costs for each of the 44 activities.

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[3] The default project network is based on the project discussed in Chap. 4 but duration and cost combinations changed to other settings to model the time/cost trade-offs.

[4] No panic, it is only a game!

Table 3.1 An activity list for the PSG project with their time/cost trade-offs

ID	Activity description	Time (days)	Cost (€)
Construction activities at the water production center			
1	Obtain building license for architecture	(7)	(2,000)
2	Find contractor for architecture	(13)	(1,000)
3	Obtain environmental license	(10;11;12;13;14;15;16;17)	(7,970;7,650;7,400;7,200;7,036;6,900;6,784;6,684)
4	Execution of architectural work	(13;14;15;16)	(6,066;5,580;5,400;5,246)
5	Design equipment	(31;33)	(38,064;36,968)
6	Negotiations high voltage cabine (HVC)	(2;3)	(1,300;966)
7	Specification/Public tender/Fabrication	(12;14;15;16;19;20;21;22)	(8,000;7,822;7,600;7,500;7,332;7,262;7,200;7,142)
8	Execution	(20;21;22)	(7,500;7,352;7,222)
9	Additional work on cables for HVC	(14;15;16;17;19)	(17,570;17,332;17,124;16,940;16,630)
10	Updating existing high pressure room	(22)	(1,500)
11	Constructing pipes between installations	(11;12;13;14;15)	(100,908;93,332;86,922;81,428;76,666)
12	Coming into operation	(17;18;19)	(20,764;20,110;19,526)
Construction activities outside the water production center			
	Pipes from WPC to Eeklo		
13	First draft design	(10;11;13;14;15;16)	(40,000;38,180;35,384;34,284;33,332;32,500)
14	Find permission/contractor and construction pipeline	(15;16;17;18;19;20;21;22;23;24)	(39,332;37,250;35,410;33,776;32,314;31,000;29,808; 28,726;27,738;26,832)
15	Design	(11;12;13;14;15;16)	(15,544;15,166;14,846;14,570;14,232;14,124)
16	Find permission	(13;14;15;16;17;18;19)	(63,460;60,714;58,332;56,250;54,410;52,776;51,314)
17	Connection electricity	(15)	(7,500)
18	Specification equipment	(28;29;30;31;32;33;34; 35;36;37;38;39;40;41)	(70,000;68,274;66,666;65,160;63,750;62,424;61,176; 60,000;58,888;57,836;56,842;55,896;55,000;54,146)
19	Delivery equipment	(3;4;5)	(1,932;1,600;1,400)
20	Execution	(3)	(4,000)

(continued)

Table 3.1 (continued)

ID	Activity description	Time (days)	Cost (€)
21	Fitting in communication system	(2;3)	(1,300;966)
22	Coming into operation	(17;18;19;20)	(12,822;12,666;12,526;12,284)
	Constructing pumps at Zelzate		
23	Design for connection electricity	(11;12;13;14;15;16;17;18)	(9,818;9,410;9,230;9,000;8,800;8,624;8,479;8,332)
24	Connection electricity	(8;9;10;11;12;14;15;16;17;18)	(16,000;15,332;14,800;14,362;14,000;13,482;13,200;13,000; 12,822;12,666)
25	Design/specification/delivery	(9;10;11;12;13;14;15;16;17;18)	(24,888;24,400;24,000;23,666;23,384;23,142; 22,932;22,750; 22,588;22,444)
26	Execution/coming into operation	(1)	(300)
	Constructing pumps and water tower at Eeklo		
27	First draft design	(13;14;15;16;17;18;19;20;21;22)	(18,538;18,284;18,066;17,874;17,704;17,554;17,420;17,300; 17,190;17,090)
28	Design	(15;16;18;19;20;21)	(14,532;14,374;14,110;14,000;13,900;13,808)
29	License request	(14;15;16;17;18;19;20;21;22)	(15,142;15,000;14,870;14,764;14,666;14,578;14,500;14,428; 14,362)
30	Specification and public tender	(16;17;18;20;21;23)	(21,750;21,528;21,332;21,000;20,856;20,608)
31	Environmental license and notification VLAREM	(15;16)	(18,400;18,250)
32	Realisation	(12;13;14;16;18;19)	(25,832;25,384;25,000;24,374;23,888;23,684)
33	Design/specification and request offer	(13;14;15;16;17;18;19;20;21)	(13,152;13,000;12,866;12,750;12,646;12,554;12,472;12,400; 12,332)

34	Execution	(14;15;16;17;18)	(27,284;27,066;26,874;26,704;26,554)
35	Coming into operation	(12;15;17)	(19,832;19,266;19,000)
	Constructing pumps at Waarschoot		
36	First draft design	(9;10;11;12;13;14;15;16;17;18)	(14,888;14,600;14,362;14,166;14,000;13,856;13,732;13,624;13,528;13,444)
37	Design	(15;16;17)	(50,000;48,750;47,646)
38	File constructing license	(16;17;18)	(15,124;14,940;14,776)
39	Specification	(12;14;16;18;20;21)	(18,166;17,570;17,124;16,776;16,500;16,380)
40	File environmental license	(14;15;16;17;18;19;20)	(7,856;7,732;7,624;7,528;7,444;7,374;7,300)
41	Realisation	(15;17;18;19;21;22)	(18,666;17,882;17,554;17,262;16,760;16,544)
42	Design	(16;17;18;19;20)	(32,374;32,116;31,888;31,684;31,500)
43	Execution	(17;18;19;20;21;22)	(14,940;14,776;14,630;14,500;14,380;14,272)
44	Coming into operation	(10)	(1200)

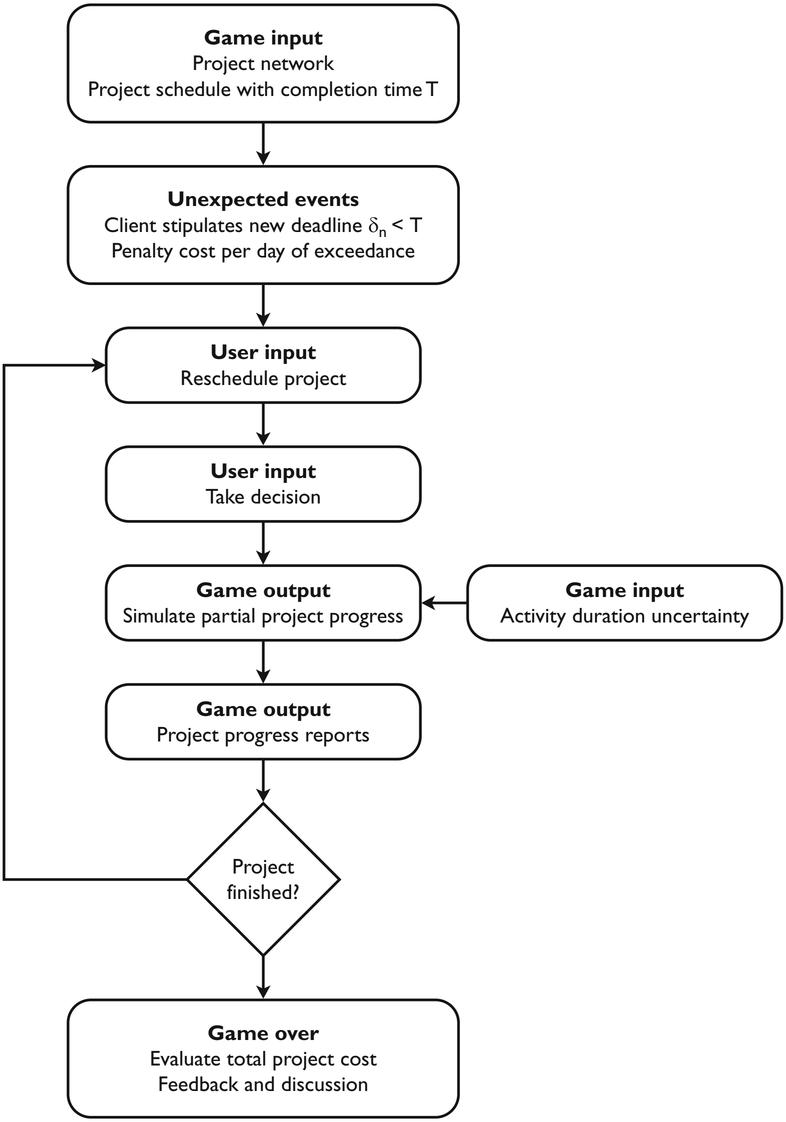

Fig. 3.6 The simulation process of the game

Unexpected events: At the start of the game, it is assumed that the manager faces a new target deadline δ_n, earlier than the project duration as initially proposed. If the project is not completed by this target deadline, a penalty cost will be imposed for each day of overrun. Shortening the entire project to bring the last project activity to completion by the target deadline may be accomplished by the expenditure of money, where necessary, to shorten various activities throughout the network.

The way money is spent (for overtime, additional workers, extra machinery, etc.) is not specified in this game.

Reschedule the project: Each project management team (i.e. the game user) is responsible for scheduling new activity durations, so that the project is completed at the lowest possible cost, where total cost is the sum of activity costs and delay costs. Consequently, the game focuses on the deadline problem of the time/cost trade-off problem, which involves the scheduling of project activities in order to minimize the total cost of the project while meeting a target deadline δ_n. Users have to select new activity modes for a subset of the project activities trying to complete the project schedule on or before the new target project deadline, aiming at minimizing the total project cost. Player decisions will establish new planned durations for some activities and will, therefore, change both the planned completion time of the project and its total cost. Decreasing activity durations will increase activity costs. The maximum activity cost for the project would result if all activities were planned at their shortest duration (the crash duration). Minimum activity cost, on the other hand, results when all activities have their longest duration (the normal duration). The difference between these two costs is the amount of resources that can be influenced by the management team's decisions.

Take decision: Upon a decision made by the user, the game simulates partial fictitious project progress. Since reality is fed with uncertainty, the game simulates uncertainty in the activity durations, leading to a project completion, which might differ from the expected project completion set by the user. These factors beyond the control of the user might mess up their original time and cost estimates of the project, and need to be carefully reviewed in order to bring the project back on track.

Evaluate project progress: After each decision, the computer will simulate the passage of a number of working days (execution phase, from t_i to t_{i+1} in Fig. 3.7) and will provide management with a list of all activities completed in that time period. PSG generates partial intermediate project progress reports indicating where changes in the original schedule took place. These reports, along with the Gantt

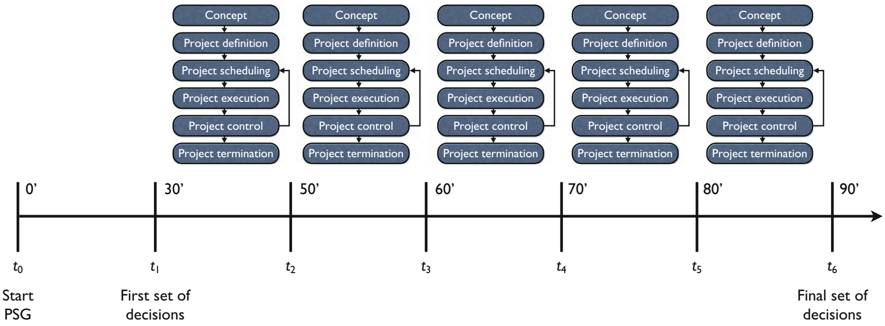

Fig. 3.7 The six decision moments of PSG

chart, must be used by the users to evaluate intermediate project progress and to adapt their previously made decisions. The computer will provide an explanation of any delays or early finishes that may have caused an activity to take a different duration than was scheduled by the project team. Before any set of decisions, the management team can change the scheduled duration for any activity that has not been completed. Obviously, the duration of a completed activity can no longer be altered by a management decision. This cycle of user decisions and project progress is repeated until the project is finished. Figure 3.7 gives a graphical illustration of the six different sets of decision steps in the game with the allocated time that a player receives to prepare his/her decision. The simulation ends after a predefined number of decision steps, within a predefined maximal allowable time limit. The default number of decision steps is equal to six, which need to be made within a 90 min time limit, but this can easily be changed by the teacher of the game.

Because of the large number of activities and huge amount of time/cost data needed during the scheduling task, a computer is used for the analysis. At any time it is possible to save and simulate scenarios before making a periodic decision, to return to the settings of the last decision, or to the settings of former saved scenarios.

3.3.4 Access to PSG Using ProTrack

The Project Scheduling Game can be accessed using the project scheduling tool ProTrack, which is discussed in Chap. 15. The best known solution for a given project can be obtained by submitting the project data to ProTrack's support webpage, using the serial number of the software version (only accessible by the teacher who needs a full version of ProTrack and not by users of the game). Moreover, teachers are encouraged to construct their own PSG data and submit their work on this support page to distribute with other PSG teachers. More details and specific features will be briefly discussed in Sect. 15.6.

3.4 Educational Approach

3.4.1 Simulation Seminar and Target Group

A traditional PSG session consists typically of three parts: a general introduction to the critical path method and the features of the project, the 90-min simulation (see previous section) and a closing part in which the distinct strategies used by the participants are discussed. The game focuses on the characteristics of allocating a scarce nonrenewable resource (money) to establish activity crashing, as well as on all basic project scheduling features (activity networks, earliest and latest start schedules, activity slack, etc.) of a large real-life project as discussed in Chap. 2.

It illustrates the difficulties a project manager faces when reactively scheduling and monitoring a large project. The game is particularly interesting for project managers, project schedulers and project team members and can be played individually or in groups of two or three participants.

3.4.2 *Teaching Process*

Each project management team should study the starting position and consider alternative courses of action for meeting the new required project completion date. While a complete analysis of the network is not essential at this point, the group should at least identify critical and subcritical paths and carefully investigate activities that are likely to be completed during the first decision report period (see Fig. 3.7). Once a decision has been made, activities completed during that period cannot be changed. During the simulation, the player is continuously confronted with a number of valuable concepts used in project scheduling, such as the earliest activity start/finish, the latest activity start/finish, the activity slack and the deadline slack. He or she must incorporate information with respect to these concepts to make periodic decisions based on a Gantt chart. Figure 3.8 shows the working screen of the player (the Gantt chart) on which decisions can be made. This screen shows:

- Activities of the current critical path of the resulting schedule.
- Possible changes in the activity duration (i.e., the activity time/cost trade-off).
- Activity slack.

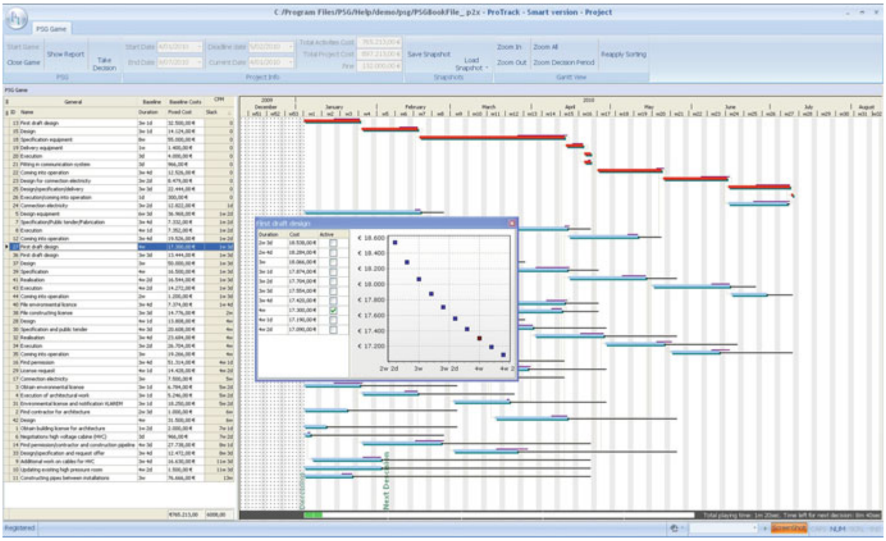

Fig. 3.8 The PSG Gantt chart in ProTrack

- The current decision moment.
- Expected project completion and the corresponding cost of the current schedule.

3.4.3 Performance Evaluation

Players are evaluated on the basis of the total cost of their final schedule. As stated earlier, total project cost is made up of the sum of the delay cost and the planned activity costs. This is illustrated in Fig. 3.9, which shows the complete optimal time/cost profile (the lowest possible cost for each possible completion time). The decreasing cost values when the project completion increases is the result of the time/cost trade-offs in the individual project activities. The increasing cost values from a certain project completion on is due to the penalty that needs to be paid when the project deadline δ_n is exceeded. Due to the combination of these two costs, players who are able to schedule the project within the target deadline δ_n do not necessarily generate the best overall schedule. Indeed, depending on the value of the penalty cost, it can be advantageous to schedule the project with a completion time δ_n^* longer than the target deadline δ_n, resulting in a penalty cost for each day overrun, but at a lower total cost. During the final discussion part of the session, the game players will be confronted with this result. Note that the final result of each participant can only lie on or above the optimal time/cost profile of Fig. 3.9.

3.4.4 Game Discussion

In the discussion following the game, performance of the teams is compared and participants are asked to describe the strategies they have followed. This leads them to a clear understanding of the meaning of the critical path and the impact of crashing activities on the critical path. Confronting the participants with the

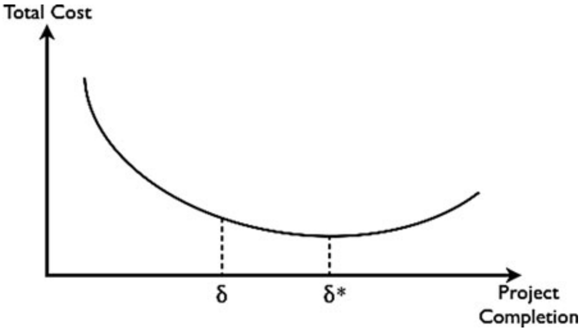

Fig. 3.9 The complete time/cost profile of the PSG project

minimum time/cost profile (as in Fig. 3.9) has proven to be very useful in this discussion.

Comparison of the results of the teams that have developed a clear strategy and those that have adopted a trial and error approach to the scheduling task illustrates the value of project scheduling techniques. Moreover, one typically observes that some teams try to optimize the project schedule over the entire project horizon at each decision phase, whereas other teams tend to focus on the first decision period only. The advantage of the former approach (reaching an optimal schedule) is then weighted against the advantage of the latter (maintaining stability in the project schedule and reaching higher efficiency in scheduling). The discussion may then turn towards the value of sophisticated scheduling in projects with high uncertainty.

The PSG is not unique. A well-known comparable game is CPSim (Piper 2005). CPSim is adapted from an exercise called CAPERTSIM that was developed by North American Aviation, Inc., Autonetics Education and Training Department. CAPERTSIM was available from the IBM SHARE library, and was adapted by the Harvard Business School in 1974 and renamed PLANETS II (*pla*nning and *net*work *s*imulation). The difference between PSG and the traditional project scheduling games, however, is the opportunity PSG provides to be played with any realistic project network tailored to the needs and wishes of the game players. The PSG can easily be extended to another project by simply changing the input file of the network under study. This makes it possible to tune the training to the participants' needs and to make the game very recognizable to the participant.

3.4.5 PSG as a Research Tool

Although the PSG is mainly described as an educational tool, it can, however, be used as a research tool. Experiments can be easily set up in which project managers schedule a project network with the game software. In these experiments, the software will observe the behavior of the managers and their preferences and strategies followed while repetitively scheduling the model. ProTrack's PSG will monitor and register all actions taken by the participants and provide a log file to the teacher. These log files can be analyzed to detect certain patterns or clusters of strategies leading to a similar output performance. Comparing performances across teams might allow the user to gain better understanding of the value of distinct project scheduling routines, under distinct types of projects and project environments. For example, it will be explored whether some scheduling strategies are more suited in project environments with low or high uncertainty.

The risk of the project can also be changed manually by the teacher of the game. While the participants have no idea about real project durations (which might differ from their chosen activity duration), the teacher can create alternative risk versions for different groups, allowing to investigate the influence of higher risk (activity duration uncertainty) on the overall performance of the different teams.

3.5 Conclusions

In this chapter, a project scheduling game for the time/cost trade-off scheduling problem, known as the critical path method (CPM), has been presented. The project is a real-life project for a water production center in order to increase the production capacity of purified water. The individual player is presented with the task of scheduling the activities in time, taking into account the total project costs by carefully allocating money to a particular activity. In doing so, the player has six decision moments in which he or she decides about the duration and corresponding cost of each network activity. After the simulation, the total project cost of the resulting schedule is used as a performance evaluation. The ultimate target of the game is to bring the manager in contact with the different concepts of project scheduling in a practical way, to confront the manager with the inherent complexity that is involved in project scheduling, and to create an incentive to rely on algorithmic procedures or at least on state-of-the-art scheduling principles studied at different research institutes. Indeed, the game clearly illustrates that the scheduling phase of the project life cycle involves a series of decisions which requires a good knowledge about basic project scheduling techniques and a thorough understanding of the impact of decisions on the overall performance of the project.