

## TIME-COST PROJECT MANAGEMENT WITH SOLVER

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**Abstract.** According to the definition provided by the Project Management Institute the time and cost constitute two crucial elements of the project management (PM). There are many computer tools supporting the project time and cost management (e.g. SAS/OR Project Management, Primavera Cost Manager, Autotask Pro), but this software does not have all functionalities necessary in the project decision-making process. Therefore, the purpose of this paper is to spur teachers, students and managers to use optimization softwares such as the Excel Solver in the PM. This article deals with time-cost problems that project managers are trying to solve and presents the Excel Solver as an extremely useful tool in project management, optimization and simulation. After a discussion concerning the time-cost project analysis and the project network construction, the author demonstrates how to mathematically model and solve a project problem with the aid of the Excel Solver. At the end the results are interpreted. Benefits of using this optimization tool in project time-cost management are numerous. Solver is designed both for small and complex projects. It yields the optimal solution as well as many what-if-analysis results. Thus, the author demonstrates how the project manager can take advantage of the range information and dual values (reduced costs and shadow prices) to check the consequences of changing different project's parameters and to set the intervals (e.g. for the unit shortening costs or the normal activity times) for which a given optimal schedule does not change. The author also argues that the Solver may successfully support the reactive and proactive project management, because in contradiction to traditional project management softwares, it easily generates brought up to date optimal solutions.

**Keywords:** project time-cost management, network, project crashing, shortening cost, Excel Solver, simulations, what-if analysis, proactive and reactive scheduling.

**Jel classification:** A2, C61, C63, D29, 022.

### 1. Introduction

The project is a temporary endeavor with a defined beginning and end undertaken to meet unique objectives, typically to bring about beneficial change or added value. Nowadays the project management is a very known and explored discipline of planning, organizing, securing, leading and controlling resources to achieve specif-

ic goals. The nine knowledge project management areas distinguished in the Project Management Body of Knowledge (PMBOK) are as follows: Project Integration Management, Project Scope Management, Project Time Management, Project Cost Management, Project Quality Management, Project Human Resource Management, Project Communications Management, Project Risk Management and Project Procurement Management (Duncan 1996). This contribution deals with two fields aforementioned: Time and Cost Management. The first one includes activity definition and sequencing, activity resource and activity duration estimating, schedule development and control. The second one is connected with cost estimating, budgeting and control (PMBOKGuide 2004). The time and cost are, beside the scope, the main constraints of the project management triangle.

Both disciplines are extremely related to the TCTP Analysis, i.e. Time-Cost Trade-off Project Analysis (De *et al.* 1995; 1997; Demeulemeester *et al.* 1996). This domain mainly serves to evaluate the impact of increasing or decreasing the level of resources on the project completion time and to find the cheapest or the shortest way of performing the whole project. Such a skill is very helpful in the project management. In the TCTP Analysis one might consider overtime, second shifts, or changing equipment to make some work proceed faster. The results of the TCTP Analysis show which activity durations should be changed to gain the intended outcomes.

There are many computer tools supporting the project time-cost management and the project management as a whole. Nevertheless, it is worth emphasizing that the existing management software (e.g. SAS/OR Project Management, Autotask Pro, Primavera Cost Manager, Quick Gantt, Team Manager, Open Plan, Project Simulation Game, Planets, MS Project, Waterfall, Easy projects, OnTime) is rather designed to: plan the structure of the project, set the critical path(s) (i.e. the longest necessary path through a network of activities when respecting their interdependencies), evaluate the cost of activities depending on the level of resources, compare planned project completion costs to the final ones, calculate the costs borne by particular divisions, assign activities to people with appropriate skills etc., but they actually do not allow to solve time-cost optimization problems described above (Dudzińska-Baryła 2008; Vanhoucke *et al.* 2005).

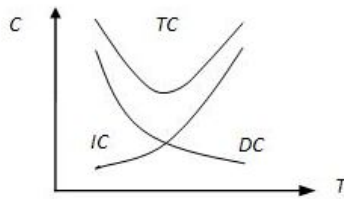
Therefore it is recommended to use an optimization software which is able to find optimal solutions, to generate results needed in the sensitivity analysis and to allow the project manager to make quick time-cost simulations. The Solver, which is an Add-In of Microsoft Excel located under “Tools” of the main menu, is a software which seems to meet all essential requirements. MS Excel Solver finds applications in many decision problems and it is used by practitioners, academic teachers and students as well, but, in my opinion, it is not sufficiently exploited in the project management.

The remainder of the paper is organized as follows. In Section 2, the time-cost project and the project network topics are discussed. A time-cost project problem is presented and mathematically formulated in Section 3. The problem is solved by

Excel Solver in Section 4. The results generated in the spreadsheet and in additional reports are explained in Section 5. Finally, advantages of using Excel Solver in project time-cost management are gathered in Section 6.

## 2. Time-cost trade-off project analysis

In TCTP problems the trade-off occurs between the project completion time ( $T$ ) and the amount of non-renewable resources, i.e. money, which constitute the total cost of the project. The total cost ( $TC$ ) includes direct ( $DC$ ) and indirect ( $IC$ ) costs. The first category concerns costs related directly to the completion of activities (e.g. salaries, travel, raw materials, equipment) and their compression. Activity durations are bounded from below (crash duration  $t^c$ ) and from above (normal duration  $t^n$ ). The shortening of a given task requires the allocation of more resources. Indirect costs are assigned to the project as a whole. They include, among other things, office space, taxes, insurance, management and penalty costs. The project manager bears penalty costs when the project completion time is delayed. When the project completion time increases, indirect costs increase as well but direct costs decrease (Fig. 1). As we see the Time-Cost Tradeoff helps the project manager to find the sweet-spot between increasing costs of specific activities and decreasing overall project costs (Anholcer, Gaspars-Wieloch 2011). There are many heuristic and exact algorithms (e.g. Anagnostopoulos 2002; De *et al.* 1995; Diaby *et al.* 2011; Gaspars-Wieloch 2009; Halman *et al.* 2009; Ke *et al.* 2012; Mohanty *et al.* 2011, Srivastava *et al.* 2010) designed for the TCTP Analysis.



**Fig. 1.** Project time-cost curves

The main problems considered are as follows ( $X$  signifies the vector of activity durations, Skutella 1998): 1) minimizing project costs within a project deadline or target time  $T^d$  (Deadline Problem, Eq. (1)-(2)), 2) minimizing project time within a specified budget  $C^b$  (Budget Problem, Eq. (3)-(4)):

$$C(X) \rightarrow \min \tag{1}$$

$$T(X) \leq T^d \tag{2}$$

$$T(X) \rightarrow \min \tag{3}$$

$$C(X) \leq C^b \tag{4}$$

We will assume that the structure of each project may be represented by a network. The best known network presentation techniques are called AON (activities-on-nodes) and AOA (activities-on-arcs). In the first approach, nodes (vertices) show activities (tasks) and arcs – the precedence relationship. In the second one, arcs indicate tasks and nodes – events, i.e. the beginning and/or the end of an activity. In this paper the AOA technique is used. The AOA rules are given in (Sikora 2008; Gaspars-Wieloch 2009). The set  $E$  of arcs consists of  $m$  arcs  $e_1, \dots, e_m$ , while the set of nodes  $V$  consists of  $n$  nodes  $v_1, \dots, v_n$ . Each arc  $e_i$ ,  $i=1, \dots, m$  is labeled by some positive natural number  $t_i$ , i.e. the duration of the respective activity. For convenience we often index the arc by  $e_{jk}$ , where  $j=1, \dots, n-1$  and  $k=2, \dots, n$  are the indices of the starting and end node of the arc, respectively (see figure 2). In addition, for each arc we define a non-decreasing sequence  $C^{(i)} = (c_{k_i}^{(i)})_{k_i=1}^{K_i}$  of real numbers representing the shortening cost (cost slope), where  $c_{k_i}^{(i)}$  is the cost of reducing the duration of the  $i$ -th activity by the  $k_i$ -th unit and  $K_i < t_i$  (one may shorten an activity at most  $(t_i^n - t_i^c)$  times). The earliest time of the event  $j$  (the earliest time at which the node  $j$  can be reached such that all its preceding activities have been finished) is denoted by  $t_j^I$  ( $t_n^I$  being equal to the minimum completion time of the project, i.e.  $T^*$ ). The latest time of the event  $j$  (the latest time that the node  $j$  can be left such that it is still possible to finish the overall project within the minimum completion time) is denoted by  $t_j^{II}$ . Finally, the slack time of activity  $e_{jk}$  (also called the total time reserve or the float time) is denoted by  $f_{jk} = t_k^{II} - t_j^I - t_{ij}$ .

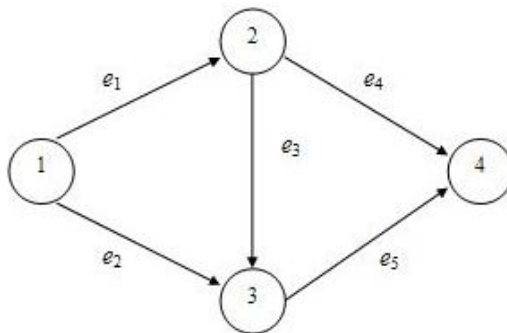


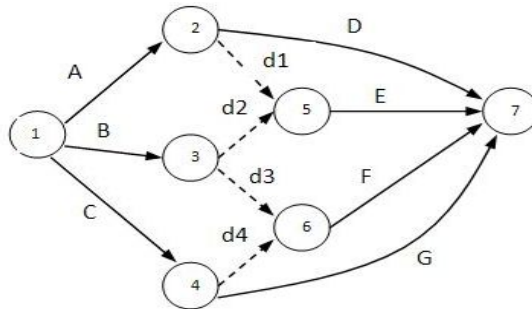
Fig. 2. Sample network

### 3. Example – data and optimization model

Let us analyze the following time-cost project problem. The project *Cosmos* includes 7 tasks. The structure of the project and the characteristics of each activity are presented in Table 1. The daily indirect cost is equal to 9 000\$. The project manager intends to find a schedule with a completion time not longer than 15 days.

**Table 1.** Characteristics of the project *Cosmos* (Source: compiled by the author)

Activities	A	B	C	D	E	F	G
Predecessors	-	-	-	A	A,B	B,C	C
Normal duration (days)	7	9	11	10	8	6	5
Crash duration (days)	5	8	9	7	6	6	4
Unit shortening cost (1000 \$)	2	3	1	2	3	-	2
Execution cost (1000 \$)	10	12	16	15	9	10	7



**Fig. 3.** Network (project *Cosmos*)

There exist many time variants satisfying this constraint and they may be easily generated by various project management computer tools, but imagine that the project manager is willing to choose only the cheapest way of performing all the tasks within 15 days. Furthermore, he or she is interested in making a what-if analysis in case of some deviations between the schedule planned and the schedule executed (Novas, Henning 2010; Vonder *et al.* 2006; 2007). In order to solve this problem using Solver three steps are required: 1) present the structure of the project by means of a network, 2) formulate the problem in form of an optimization model, 3) introduce the data and formulas in an Excel spreadsheet.

The AOA network for the project *Cosmos* is given in Figure 3. Dummy activities (used to correctly demonstrate the predecessors) are shown by dotted lines. Notice that the unit shortening cost for each task is constant, which makes the

problem very easy to formulate. Issues concerning the mathematical modeling of time-cost project problems are comprehensively treated in (Anholcer, Gaspars-Wieloch 2011; Gaspars-Wieloch 2008, 2009, 2010; Lamberson, Hocking 1970; Liu *et al.* 1995; Moussourakis, Haksever 2004; Sikora 2008; Trzaskalik 2008). Now let us formulate the optimization model for the problem described above:

$$2y_A + 3y_B + 1y_C + 2y_D + 3y_E + 2y_G + 79 + 9x_7 \rightarrow \min \quad (5)$$

$$x_2 - 7 + y_A \geq x_1 \quad (6)$$

$$x_3 - 9 + y_B \geq x_1 \quad (7)$$

$$x_4 - 11 + y_C \geq x_1 \quad (8)$$

$$x_5 \geq x_2 \quad (9)$$

$$x_5 \geq x_3 \quad (10)$$

$$x_6 \geq x_3 \quad (11)$$

$$x_6 \geq x_4 \quad (12)$$

$$x_7 - 10 + y_D \geq x_2 \quad (13)$$

$$x_7 - 8 + y_E \geq x_5 \quad (14)$$

$$x_7 - 6 + y_F \geq x_6 \quad (15)$$

$$x_7 - 5 + y_G \geq x_4 \quad (16)$$

$$x_7 \leq 15 \quad (17)$$

$$0 \leq y_A \leq 2 \quad (18)$$

$$0 \leq y_B \leq 1 \quad (19)$$

$$0 \leq y_C \leq 2 \quad (20)$$

$$0 \leq y_D \leq 3 \quad (21)$$

$$0 \leq y_E \leq 2 \quad (22)$$

$$y_F = 0 \quad (23)$$

$$0 \leq y_G \leq 1 \quad (24)$$

$$x_1, x_2, \dots, x_7 \geq 0 \quad (25)$$

where  $x_1, \dots, x_7$  denote the time of the events 1 – 7 and  $y_A, \dots, y_G$  signify the number of time units by which a given activity is shortened. Thanks to the equation (5) the total cost is minimized. The total cost includes shortening activity costs ( $2y_A + 3y_B + 1y_C + 2y_D + 3y_E + 2y_G$ ), execution activity costs (79) and indirect costs ( $9x_7$ ). The constraints (6) – (16) guarantee that the event finishing a particular task will always occur after the event starting this task. Thanks to the formula (17) the project completion time will not exceed 15 days. The target of the restrictions (18) – (24) is to bound the values of  $y$  from below (it is always zero) and above (this parameter is equal to the difference between the normal time and the crash time).

Now one may easily introduce the data in the spreadsheet and solve the problem using the Solver (Section 4).

#### 4. Problem solving with Microsoft Excel Solver

Before introducing data it is worth emphasizing that the three things that must be specified for the Solver tool are the target cell, the adjustable cells, and the constraint cells (for more guidelines see [www.solver.com](http://www.solver.com)).

M20														M24																		
A	B	C	D	E	F	G	H	I	J	K	A	B	C	D	E	F	G	H	I	J	K											
<b>PARAMETERS</b>														<b>PARAMETERS</b>																		
activities														activities																		
A	B	C	D	E	F	G					A	B	C	D	E	F	G															
normal time														normal time																		
	7	9	11	10	8	6	5					7	9	11	10	8	6	5														
crash time														crash time																		
	5	8	9	7	6	6	4					5	8	9	7	6	6	4														
shortening cost														shortening cost																		
	2	3	1	2	3		2					2	3	1	2	3		2														
execution cost														execution cost																		
	10	12	16	15	9	10	7					10	12	16	15	9	10	7														
<b>VARIABLES</b>														<b>VARIABLES</b>																		
x1	x2	x3	x4	x5	x6	x7					x1	x2	x3	x4	x5	x6	x7															
	0	0	0	0	0	0	0					0	5	8	9	8	9	15														
yA	yB	yC	yD	yE	yF	yG					yA	yB	yC	yD	yE	yF	yG															
	0	0	0	0	0	0	0					0	1	2	2	1	0	0														
<b>CONSTRAINTS (6) - (16)</b>														<b>CONSTRAINTS (6) - (16)</b>																		
6)	7)	8)	9)	10)	11)	12)	13)	14)	15)	16)	6)	7)	8)	9)	10)	11)	12)	13)	14)	15)	16)											
LHS														LHS																		
	-7	-9	-11	0	0	0	0	-10	-8	-6	-5											-2	0	0	8	8	9	9	7	8	9	10
RHS														RHS																		
	0	0	0	0	0	0	0	0	0	0	0											0	0	0	5	8	8	9	5	8	9	9
<b>CONSTRAINTS (18) - (24)</b>														<b>CONSTRAINTS (18) - (24)</b>																		
RHS (normal time - crash time)														RHS (normal time - crash time)																		
	2	1	2	3	2	0	1															2	1	2	3	2	0	1				
<b>OBJECTIVE</b>														<b>OBJECTIVE</b>																		
shortening														shortening																		
	0																					12										
execution														execution																		
	79																					79										
direct costs (shortening + execution)														direct costs (shortening + execution)																		
																																91
indirect costs														indirect costs																		
																																135
target cell (direct costs + indirect costs)														target cell (direct costs + indirect costs)																		
																																228

**Fig. 4.** Spreadsheet with inserted data (project *Cosmos*) and optimal results generated by Microsoft Excel Solver (project *Cosmos*)

The problem analyzed has 14 decision variables and 20 constraints. The way how data should be inserted in the spreadsheet is demonstrated in Figure 4 (on the left). The target cell is F31 and rows 14, 16 are dedicated for the adjustable cells. Notice that cells of the line 20, 22 and 25, and cells B27, B28, F29, F30, F31 contain formulas. The optimal results are given in Figure 4 (on the right), 5 (Sensitivity Report) and 6 (Limits Report). Whenever Solver finds a solution, additional reports are produced: Sensitivity, Limits, Answer, Performance and Program Report, but the two first reports are the most important from the project manager's point of view. That is why we will only discuss these two elements in Section 5.

## 5. Results and Solver reports interpretation

According to the Figure 4 (on the right) the project manager should shorten the activities C and D by 2 days (cells C16 and D16), and shorten the activities B and E by 1 day (cells B16 and E16). That means that the activities should last 7, 8, 9, 8, 7, 6, 5 days respectively. This strategy will allow the project manager to complete the whole project in 15 days (cell G14) with the lowest cost equal to 226 000 \$ (cell F31). Shortening costs amount to 12 000\$. All these data are located in the main spreadsheet. Now let us check the results presented in Solver reports.

Adjustable Cells							
Cell	Name	Final Value	Reduced Cost	Objective Coefficient	Allowable Increase	Allowable Decrease	
\$A\$14	x1	0	9	0	1E+30		9
\$B\$14	x2	7	0	0	0		2
\$C\$14	x3	8	0	0	1E+30		0
\$D\$14	x4	9	0	0	1E+30		3
\$E\$14	x5	8	0	0	1E+30		0
\$F\$14	x6	9	0	0	1E+30		3
\$G\$14	x7	15	0	9	4		3
\$A\$16	yA	0	0	2.000000001	1E+30		0
\$B\$16	yB	1	0	3	0	1E+30	
\$C\$16	yC	2	-3	1	3.000000001	1E+30	
\$D\$16	yD	2	0	2	0		2
\$E\$16	yE	1	0	3	3	0	
\$F\$16	yF	0	-4	0	1E+30		4
\$G\$16	yG	0	2	2.000000001	1E+30	2.000000001	

Constraints							
Cell	Name	Final Value	Shadow Price	Constraint R.H. Side	Allowable Increase	Allowable Decrease	
\$A\$20	LHS	2.6501E-10	2	0	1		2
\$B\$20	7)	3.0519E-10	3	0	1		1
\$C\$20	8)	3.4538E-10	4	0	0		1
\$D\$20	9)	8	0	0	1	1E+30	
\$E\$20	10)	8	3	0	1		1
\$F\$20	11)	9	0	0	1	1E+30	
\$G\$20	12)	9	4	0	0		1
\$H\$20	13)	7	2	0	1		2
\$I\$20	14)	8	3	0	1		1
\$J\$20	15)	9	4	0	0		1
\$K\$20	16)	10	0	0	1	1E+30	

Fig. 5. Sensitivity Report (project *Cosmos*)

The Sensitivity Report (Figure 5) provides classical sensitivity analysis information for both linear and nonlinear programming problems. The problem considered is a linear one and in such a case the report contains: 1) dual values for non-basic variables (called Reduced Costs), 2) dual values for binding constraints (called Shadow Prices) and range information (allowable increase and decrease). When an upper or lower bound on a variable is binding at the optimal solution, a nonzero Reduced Cost appears in the “Adjustable Cells” section of the report. The Reduced Cost measures the increase in the objective function’s value per unit increase in the variable’s value. For the project manager:

- the Reduced Cost for  $x_1$  equal to 9 means that if the project starts with a one-day delay the minimal total cost will increase by 9 000\$,



- the Reduced Cost for  $y_C$  equal to -3 means that if it was possible to shorten the task C more than twice, an additional unit shortening of this activity would decrease the minimal total cost by 3 000\$,
- the Reduced Cost for  $y_G$  equal to 2 means that a unit shortening of the activity G will increase the total cost by 2 000\$,
- the Reduced Cost for  $y_A$  equal to 0 means that there exist at least one more optimal plan, i.e.  $(y_A = 2, y_B = 1, y_C = 2, y_E = 1)$ .

The Reduced Cost for the variable  $y_F$  should not be interpreted because the activity F can not be shortened and its shortening cost is not given (see Section 3).

The dual value for a constraint is nonzero only when the constraint is equal to its bound (the left and the right value of the constraint are the same). This is called a binding constraint. The dual value (Shadow Price) measures the increase in the objective function's value per unit increase in the constraint's bound. For the project manager the Shadow Price for the constraint (6) equal to 2 means that if the normal duration of the activity A was 8 days (not 7), the minimal total cost of the new optimal schedule would be  $226\ 000 + 2000 = 228\ 000$  \$ etc. Notice that we should not analyze the Shadow Price for constraints related to dummy activities because their time will be always equal to zero.

In linear programming problems the dual values are constant over a range of possible changes in the objective function coefficients and the constraint right hand sides. The Sensitivity Report includes this range information. For each decision variable the report shows the amount by which its coefficient could be increased or decreased without changing the Reduced Cost and the optimal solution. For each constraint the report shows the amount by which the constraint right hand side could be increased or decreased without changing the Shadow Price. Let us answer several potential manager's questions on the basis of the Sensitivity Report:

- 1) What will happen if the shortening cost of the activity A increases by 1000\$? Answer: The allowable increase for the coefficient  $c_A$  is equal to  $\infty$ . Thus, this modification will not change the optimal solution. Additionally, since in the optimal plan  $y_A = 0$  (non-basic variable), the minimal total cost will be still equal to 226 000\$.
- 2) Will the reduction of the shortening cost of the activity E by 1000\$ entail a modification of the optimal schedule and the minimal cost? Answer: Yes, because the allowable decrease for the coefficient  $c_E$  equals to 0.
- 3) The project manager has just realized that the shortening cost of the activity C would amount to 3 000\$ (not 1 000\$). What does it mean for the project? Answer: The allowable increase for  $c_C$  equals 3. Thus, if the cost increases by 2 000\$, the optimal solution will be the same. Nevertheless, since  $y_C = 2$  (basic variable), the total cost will be  $226 + 2 \cdot 2 = 230000$ \$.
- 4) May the project manager use the Shadow Price to set the consequences of the reduction of the normal time of the activity F by one day? Answer:

Yes, the allowable decrease of the constraint RHS (i.e. the normal time after putting the parameter on the right and variables on the left side of the constraint 15) equals 1. The total cost will be  $226 - 1 \cdot 4 = 222000\$$ .

Thanks to the Sensitivity Report the project manager can find critical (with no slack time) and non-critical activities (with a positive slack). Non-critical tasks are characterized by non-binding constraints (Figure 4, row 20 and 22) with a Shadow Price equal to 0 (in this case the activities  $d_1, d_3, G$  are non-critical).

The screenshot shows an Excel spreadsheet with the following content:

Microsoft Excel 11.0 Limits Report  
Worksheet: Time-cost problem  
Report Created: 2012-08-30 16:48:40

Target		
Cell	Name	Value
\$E\$31	target cell	226

Adjustable			Lower	Target	Upper	Target
Cell	Name	Value	Limit	Result	Limit	Result
\$A\$14	x1	0	0	226	2.65006E-10	226
\$B\$14	x2	7	7	226	7.000000001	226
\$C\$14	x3	8	8	226	8	226
\$D\$14	x4	9	9	226	9	226
\$E\$14	x5	8	8	226	8.000000001	226
\$F\$14	x6	9	9	226	9.000000001	226
\$G\$14	x7	15	15	226	15	226
\$A\$16	yA	0	0	226	2	230
\$B\$16	yB	1	1	226	1	226
\$C\$16	yC	2	2	226	2	226
\$D\$16	yD	2	2	226	3	228
\$E\$16	yE	1	1	226	2	229
\$F\$16	yF	0	0	226	0	226
\$G\$16	yG	0	0	226	1	228

Fig. 6. Limits Report (project *Cosmos*)

The Limits Report (Figure 6) provides a specialized kind of “sensitivity analysis” information. It shows a “lower limit” and an “upper limit” for each variable, which are the smallest and the largest values that a variable can take while satisfying the constraints and holding all of the other variables constant. In the project “*Cosmos*” any change of the time of particular events will yield an infeasible solution (lower and upper limits are identical). Some upper limits for variables  $y$  are higher than their lower limits. That means that the activities A, D, E, G had not reached their crash time yet.

## 6. Conclusions

The existing software supporting the project management does not have the functionality allowing the manager to optimize the time and the cost of a project on the basis of different time-cost variants for particular activities belonging to the project. This paper shows how the Excel Solver can be applied in the project time and cost management.

1. The Excel Solver allows the user to find very quickly the optimal solutions, which in the project time-cost management means the cheapest or the shortest schedule meeting all the customer's and technical requirements.
2. This paper deals with a small project, but the Solver allows to solve problems even with 8000 constraints and 8000 variables, which means that complex projects may also be considered.
3. Besides the results given in the main spreadsheet and in the reports, Solver also allows to make various simulations by significantly changing different parameters of the project problem (e.g. normal durations, shortening costs, relationships between activities) and checking the new optimal schedule, meanwhile traditional tools supporting project management only show how a parameter's modification affects the plan, but do not generate an new optimal one. This functionality is very desirable in the reactive and proactive project management (i.e. project management coping with highly dynamic and unpredictable environments) when some deviations between the plan and reality occur and it is necessary to fit immediately the schedule to the changes during the project execution (Li and Ierapetritou 2008).

Regarding the advantages aforementioned one may state that the Excel Solver is an extremely comfortable simulation and optimization tool which can successfully improve the decision-making process in the project management. The Solver answers many crucial questions within the project planning, design and execution processes, which should spur managers, teachers and students to use this tool in the project management.

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