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Practical Spreadsheet-Based Modelling for Effective Construction Project Scheduling

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ABSTRACT

Schedule and cost are traditionally considered critical factors in the effective management of construction projects. Particularly, the endemic conflicting relationship between duration and different types of cost and the need for optimal solutions is one of the most demanding problems for construction managers over time. Several commercial software packages along with open-source free to use applications are nowadays available to support project scheduling. However, these specialized software tools do not always seem to offer all the required optimization functions to facilitate the decision-making process, and a practical method is still required that could automatically produce optimal solutions, immediately answer "what-if" questions, and allow managers to conduct time-cost simulations. The paper initially displays the fundamental critical path network analysis and defines the problem of optimizing the project time-cost interrelation. Then, a spreadsheet-based formulation of a linear programming model to solve the time-cost trade-off problem is proposed and its flexible application to a medium-scale real construction project is analyzed. The work demonstrates that project planners in the construction industry can benefit immediately from easily derived rapid solutions at relatively low cost by changing the reference values of critical variables. It is also believed that this practical and automated optimization technique can contribute to the accomplishment of successful decision-making in construction project scheduling. Therefore, the paper aims at motivating construction managers to make more extensive

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ARTICLE INFO
Received: 27 August 2025 | Revised: 24 October 2025 | Accepted: 31 October 2025 | Published Online: 7 November 2025
DOI: https://doi.org/10.55121/upc.v3i2.1058

CITATION
Kantianis, D., 2025. Practical Spreadsheet-Based Modelling for Effective Construction Project Scheduling. Urban Planning and Construction. 3(2): 77–96. DOI: https://doi.org/10.55121/upc.v3i2.1058

application of spreadsheet modelling in conjunction with the built-in solving add-in algorithms to address complex time-cost trade-off relationships and, in general, to achieve more realistic project simulation and scheduling.

Keywords: Construction Project; Scheduling; Decision-Making; Mathematical Programming; Spreadsheet Modelling

1. Introduction

The Cambridge Business English Dictionary defines a project as "a piece of planned work or an activity that is finished over a period of time and intended to achieve a particular purpose" [1]. Construction is a project-based industry; a construction project is the design and production of the construction product, e.g., a building, a bridge, or a motorway [2], usually to bring about some beneficial change in society at large or added business value [3]. Traditionally, the academic field of project management is considered as one of the key disciplines of management science [4]. According to the Project Management Institute (PMI), project management includes the following ten core knowledge areas: integration management, scope management, schedule management, cost management, quality management, resource management, communications management, risk management, procurement management, and stakeholder management [5]. This paper deals with the investigation of the relationship between two of the aforementioned project management knowledge areas: schedule management and cost management—for many researchers [6,7], perhaps the two most important construction performance measures. Schedule or time management includes the definition of project activities and their execution sequence, the estimation of their required resources and execution duration, and the planning and control of the schedule. Cost management deals with the estimation of the (direct and indirect) costs of the project as well as the preparation and control of the project budget [8]. Time and cost, together with scope (technical and other requirements), constitute the project management "iron triangle" [9,10], i.e., the main constraints towards the achievement of the expected project performance or else formerly quality. These two sub-fields show a conflicting relationship, the investigation of which is one of the most important challenges for all those involved in project management [11–13], with main objectives being the assessment of the impact of increasing or decreasing the level of resources on the project end time as well as finding either the most economical or the shortest way to execute the entire project. Such information contributes significantly to the effort of project managers towards more effective decision-making [14]. In the context of improving the project time-cost relationship by speeding up some critical tasks, one could examine the adoption of several strategies such as overtime work or the introduction of additional or night shifts, the selection of different types of equipment, or the use of subcontracting [15,16].

There are several software tools that support both overall project management and specifically time-cost management [17,18]. It is worth noting, however, that both commercially available project management software (e.g., Microsoft Project®, Oracle Primavera®) and free open-source software (e.g., ProjectLibre™) do not essentially allow for quick solutions to the fundamental time-cost optimization problems [19]. Therefore, there is a need to use an optimization tool that could easily produce optimal solutions, instantly calculate the results from useful sensitivity analyses, and allow managers to effortlessly perform project simulations. Spreadsheets like Microsoft Excel® (hereinafter Excel) seem to meet all the basic requirements, finding applications in many decision-making problems in management science [20–22] and having been used for decades by professionals, academics and students, together with their add-in optimization tools, such as Excel's Solver add-in (hereinafter Solver) (www.solver.com). Notwithstanding the indicative use of Excel (Version 2510 Build 16.0.19328.20244) and Solver in this work, it is noted that the analysis can also be conducted with any other available spreadsheet software (e.g., open-source LibreOffice or OpenOffice Calc) and solver algorithm tool (e.g., OpenSolver).

The main objective of the paper is to contribute to the existing construction management literature by developing a practical and easy-to-implement spreadsheet-based linear programming (LP) mathematical technique for the solution of the time-cost trade-off problem (TCTP) in construction. Thus, the research aims at motivating construction managers towards wider application of spreadsheet-based modelling in project scheduling. The research methodological framework entails: the definition of the TCTP and its importance in effective project management; a short literature review focused on the spreadsheet-based TCTP modelling research approaches to date; the spreadsheet formulation of the proposed LP tool and the discussion of the results from its application to a real medium-scale project; derived conclusions, research limitations, and recommendations for future work.

2. Materials and Methods

2.1. Literature Review

Decision-making in construction scheduling starts prior to construction production with determining the optimal relationship between project duration and cost. This time-cost relationship is a function of the technological level of project activities, the required and available resources, and their associated costs. Optimizing this connection is usually a complex and demanding process [23]. To estimate the duration and cost of a project, experience gained from previous projects is mainly used. Initially, project planners break down the work into discrete, smaller parts (activities) to which various resources can be assigned to estimate their durations and costs. These activities are interlinked according to their technological priority constraints to design a project network. Time scheduling methods such as the critical path analysis (CPA) can be used to "solve" the network, i.e., to identify the most important activities which define its critical path [24] and to derive its completion time [25]. However, there are various combinations for the execution of project activities depending on the choices made on different types and numbers of resources. This creates a classic problem in construction management to find the "best" combination (solution) of project duration and cost parameters. Several iterations are often required to arrive at an optimal solution [26]. In public infrastructure projects, penalty clauses are commonly accepted by contractors for not exceeding the agreed contractual deadlines. In private sector projects, owners may demand a faster completion than contractually specified by offering additional fees to contractors for project expedition. On the other hand, constructors may request an earlier project delivery to avoid adverse weather conditions or to free up equipment for upcoming projects [27].

Therefore, preparing a project schedule mainly includes the following three possible objectives: i) minimizing the execution time subject to a fixed "ceiling" of available funding (or "the budget constraint" problem), ii) minimizing the total project cost based on a specified project duration (or "the deadline constraint" problem) [28] and iii) synthesizing the two previous objectives to develop an efficient profile of time-cost combinations for a set of feasible project durations [29].

The time reduction in a project can be achieved by compressing the duration of some or all its critical activities, nevertheless increasing the direct cost of required resources. However, by saving time on the project, there will be a corresponding saving on the project's indirect cost (site overhead). Thus, in construction production, balancing the increase in direct costs and the reduction in indirect costs is the subject of the project time-cost trade-off problem (hereinafter TCTP). Increasing the resources allocated to each activity reduces the duration of activities but up to a point in time where the use of additional resources does not lead to additional total cost savings in the project [30]. This point, which corresponds to the combination of the minimum total cost ("Min total cost" point on the vertical axis) and the optimal total duration ("Optimal D" point on the horizontal axis), is illustrated in **Figure 1**. "Normal D" point on the horizontal axis denotes the project duration under normal construction execution conditions, i.e., without crashing any project activity. The "Overhead" line in **Figure 1** represents the site indirect cost of the project and not the company overhead, which is the general and administrative costs not directly related to the specific project [31]. Bonuses and/or penalties may also be considered.

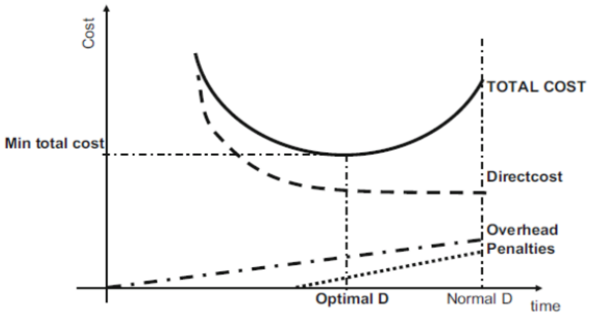

Figure 1. Typical time-cost optimization analysis graph [30].

TCTP has been studied extensively since the emergence of CPA [32]. These studies can be classified into the following three categories [33]: i) mathematical models for exact solutions, ii) heuristic procedures for near-optimal solutions, and iii) meta-heuristic algorithms for optimal or near-optimal results. Mathematical methods transform scheduling problems into mathematical models through linear, integer, or dynamic programming to accurately solve the problem [25,34,35]. However, formulating the constraints and objective functions can be time-consuming and error-prone, especially for large networks [36]. Several reviews of mathematical programming efforts are available [28,37,38]. Heuristic methods require less computational effort than exact analytical methods [39–41]. In general, heuristics provide a fast way to reach near-optimal solutions at a reasonable computational cost, but they do not guarantee optimization. Furthermore, the solutions offered do not provide a range of possible solutions, making it difficult to investigate different scenarios [25]. Subsequently, several meta-heuristic approaches were developed that search for optimal or near-optimal solutions: genetic algorithms [26,32,42–45], neural networks [46], particle swarm optimization [47,48], ant colony optimization [49–51], teaching learning-based optimization [52], and repulsion-based improved arithmetic optimization [53]. These approaches, however, require special knowledge of advanced optimization techniques and may not be practical for construction managers.

The time-cost relationship for each activity can be linear [54], piece-wise linear [23], convex [55], concave [56], quadratic [57], or discrete [58,59]. **Figure 2** presents typical linear and discrete examples. The optimization model used in the present research approximates both the direct and indirect project costs as linear functions of time, as used in the original CPA [60].

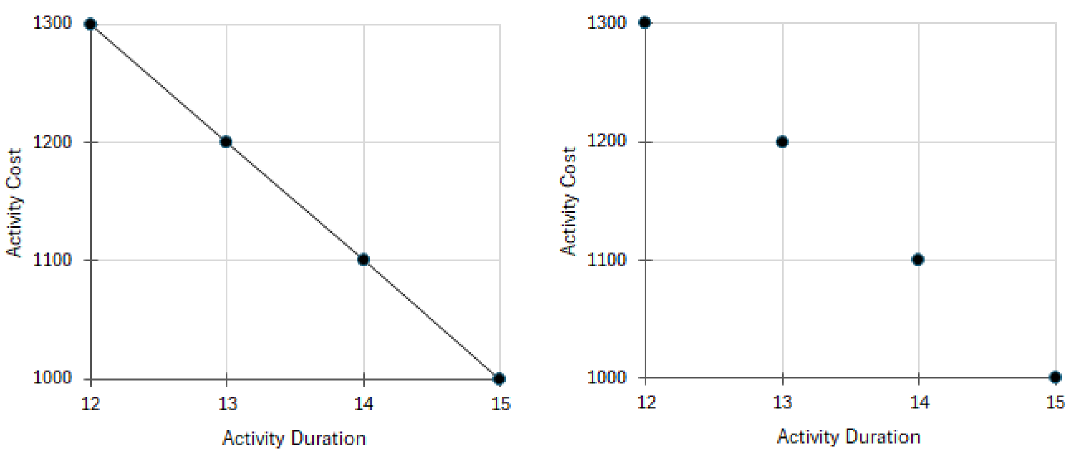

Figure 2. Example of linear (left) and discrete (right) duration-direct cost relationships.

Using spreadsheets as a flexible and practical alternative to project scheduling has gained popularity since the ’90s. This modelling approach is considered more dynamic for decision-making than traditional mathematical computations, and straightforward and less complicated compared to advanced programming languages [61]. Spreadsheets have a friendly interface suitable for model building: easy to input, capability of carrying out sensitivity analysis, transparent output, and automated report generation [62]. In construction, spreadsheets are an ideal tool for developing network models and performing CPA [63]. Pioneering relevant approaches can be found in Seal [62], Ragsdale [64], Davis [65], and Baker [63]. For the solution of TCTP specifically, a simplified spreadsheet approach was first proposed by

Hegazy and Ayed [66], followed by Ragsdale [67], Li et al. [68], and Gaspars-Wieloch [69]. Kantianis [70] recently introduced a stochastic spreadsheet-based approach to TCTP, considering statistical correlations between normal and crash durations and costs. Despite its practical potential, this short literature review shows that spreadsheet modelling still lacks wider application to construction management. Thus, the paper aims at contributing to the existing practice of construction scheduling with spreadsheet-based modelling and especially to the practical solution of TCTP.

2.2. Model Development

Current project scheduling practice usually uses networks with activities at the nodes (Activity-on-Node, AoN). This technique is more flexible and offers the possibility of a more realistic simulation of projects [71]. In an AoN project network, activities are assigned to nodes, and arcs connect the nodes, and therefore these activities to each other. A project is defined as a directed and acyclic graph G = (K, P) containing a set of interdependent activities with the required time and available resources for their completion. The structural analysis of the project provides a record of the activities as a set of K nodes and a set of P technological priority relationships between these nodes. The node set K consists of n project activities i = {1, …, n} to be scheduled, plus two auxiliary (dummy) activities of zero duration, 0 and n+1, which represent the start and finish of the project, respectively. The priority relationships are represented as pairs of activities (u, v), where: u ≠ v, stating that the start time of activity u affects the earlier start of activity v. Each activity u is assigned a duration d_u and each pair (u, v) ∈ P is assigned a time lag δ_{uv}. The time constraint is then $\delta_{uv} \leq b_v - b_u$, where: b_u and b_v are the start times of activities u and v, respectively. If (u, v) ∈ P, activity v cannot start earlier than δ_{uv} time units (usually working weeks or days) after the start of activity u. If $\delta_{uv} = d_u$, the above inequality constraint is referred to as a direct priority constraint between activities u and v, or otherwise a finish-to-start (FS) precedence relation without lag or lead. The following is a description of the steps required to analyze an AoN network using the CPA [72]: 1) calculating the earliest completion times (k_i) of the network activities through a synchronous calculation (from the start to the finish of the project) and selecting the longest path, i.e., the longest earliest completion time of the final activities determines the total duration of the project (D_p), 2) calculation of the slowest completion times (m_i) of the network activities through a counter-calculation (from the completion to the start of the project) and selection of the longest path (the final earliest completion time is the same as its earliest completion time and gives the same total project duration D_p), 3) calculation of the total slack or else float (s_i) of the activities, which is either the slowest start times minus the earliest start times ($l_i - j_i$) or the slowest finish times minus the earliest finish times ($m_i - k_i$) (both give the same result), and 4) determination of the critical activities, that is, those activities that have zero total float and determine the critical path of the project.

The definition of an AoN project network with FS immediate precedence constraints, i.e., without any leads and/or lags, that will be "compressed", assuming a linear time-cost relationship for each activity, is as follows [54]:

G a directed and acyclic graph (network), where: G = (K, P)
H set of nodes (activities) in the project network
P set of arcs connecting nodes (activities) in the project network
i project activity (node), where: i = {0, 1, …, n, n+1} ∈ K
ai normal duration of activity i ($d_i \geq 0$)
j_i earliest start time of activity i
k_i earliest finish time of activity i
l_i latest start time of activity i
m_i latest finish time of activity i
s_i total slack of activity i, where:

$$s_i = m_i - k_i = l_i - j_i \tag{1}$$

D_p project duration
N_i normal direct cost of activity i (for normal duration d_i)
N_p total direct cost of project, where:

$$N_p = \sum N_i \tag{2}$$

t_i minimum duration of activity i for maximum compression ($0 \leq t_i \leq d_i$)
r_i maximum reduction in duration of activity i, where:

$$r_i = d_i - t_i \tag{3}$$

b_i start time of activity i due to crashing ($b_i \geq 0$)
e_i end time of activity i due to crashing ($e_i \geq 0$), where:

$$e_i = b_i + d_i - w_i \tag{4}$$

w_i reduction in duration of activity i due to crashing ($0 \leq w_i \leq r_i$)
C_i additional cost of reducing duration of activity i

A_i additional cost per unit of time of reducing duration of activity i, where:

$$A_i = C_i/r_i \quad (5)$$

C_p total additional cost for project crashing, where:

$$C_p = \sum (A_i\, w_i) \quad (6)$$

O_t indirect cost (site overhead) per time unit of project execution (fixed amount)

O_p total indirect cost (site overhead) of the project, where:

$$O_p = O_t\, D_p \quad (7)$$

B_p total project cost (the sum of total direct, total crashing, and total indirect costs), where:

$$B_p = N_p + C_p + O_p \quad (8)$$

The basic (first) LP mathematical model formulation for finding the shortest feasible project duration D_p and the amount of time by which each critical activity in the project network would need to be crashed to achieve this duration, is as follows (Duration Model):

1) Objective function,

minimize $Z = D_p = e_{n+1}$ project duration, where: (9)

e_{n+1} end time of terminal (dummy) activity n+1

2) Decision variables,

b_i, w_i start times and crash times of activities i, respectively

3) Constraints,

$w_i \le r_i$	maximum reduction in activity duration i	(10)
$w_i \ge 0$	reduction in activity duration i non-negative	(11)
$b_i \ge 0$	start time of activity i non-negative	(12)
bi ≥ 0	normal duration of activity i non-negative	(13)
$b_{i+1} - b_i \ge d_i - w_i$	general constraint for activity precedence relationships	(14)

Constraints (10)–(13) are straightforward. Constraint (14) indicates that each succeeding activity i+1 cannot start before the start time b_i of its preceding activity i plus the normal duration d_i of activity i minus the crash time w_i of activity i. In other words, the difference between the start times of activities i and i+1, i.e., the Left-Hand Side (LHS) of the LP problem, must be greater than or equal to the normal time of activity i minus the amount by which the duration of activity i has been shortened, i.e., the LP problem's Right-Hand Side (RHS). Equality (9) and Inequalities (10)–(14) can be easily developed in a spreadsheet and solved with Solver.

For a modified (second) LP mathematical model formulation to determine the least costly execution sequence of activities so that the project is completed at several earliest than normal specific durations (Cost Model), the following new Objective function is required together with the addition of a new constraint for keeping each time the calculated project duration less than or equal to the selected minimum duration:

4) (New) Objective function,

minimize $Z = C_p$ otal cost for crashing the project (15)

5) (New) Constraint,

$D_p \le T_p$ minimum project duration constraint, where: (16)

T_p the required minimum project duration

Decision variables (b_i, w_i) and Constraints (10)–(14) of the basic LP model remain unaltered. The above (second) LP model (Equality (15) and Inequalities (10)–(14) and (16)) can be solved with Solver.

Finally, for another (third) modification of the LP mathematical formulation to determine the "best" project duration-cost pair, i.e., the minimum total cost and resulting optimal duration (Optimization Model), the required Objective function is now to minimize the total project cost (without the need to use previous Constraint 16):

6) (New) Objective function,

minimize $Z = B_p$ total project cost (17)

Decision variables (b_i, w_i) and Constraints (10)–(14) of the basic LP model remain unchanged. The above (third) LP model (Equality (17) and Inequalities (10)–(14)) can again be solved with Solver. The application of the above-mentioned discrete TCTP solving tools is presented in detail in the following section.

3. Results and Discussion

The threefold presented in the previous section suggested LP model (Duration, Cost, and Optimization modelling versions) is applied to the following TCTP for a private medium-sized new building project with ten main activities, which is planned to be erected in Athens, Greece. To develop and solve the problem in a spreadsheet, the required steps are: 1) the visualization of the structural analysis of the project through an AoN network and a Gantt chart, and 2) the solution of the network by applying the CPA, identifying the critical path of the project and its normal duration. The selection of the FS technological priority relationships for the execution of these activities, as well as the estimated duration for each activity, is presented in **Figure 3** (columns 2–3). These activity time estimates are based on Monte Carlo simulations using historically relevant data from similar projects previously delivered by the same building contractor. The associated formulae are demonstrated in **Figure 4**. **Figure 3** also shows the CPA results (columns 4–9). A, E and I are the critical activities of the project that determine its total duration at 13 weeks. The binary results in column 9 show "1" for critical tasks (i_c) with zero total slack (s_i), and "0" for non-critical tasks (i_{nc}) with $s_i > 0$ (column 8).

	B	C	D	E	F	G	H	I	J
1									
2	Activity i ($i = 1, \ldots, n$)	Immediate Predecessors (FS)	Normal Duration d_i	Earliest Start j_i	Earliest Finish k_i	Latest Start l_i	Latest Finish m_i	Total Slack s_i	Critical Path ($i_c = 1$, $i_{nc} = 0$)
3	A	---	2	0	2	0	2	0	1
4	B	---	2	0	2	3	5	3	0
5	C	A	3	2	5	8	11	6	0
6	D	A	6	2	8	3	9	1	0
7	E	A	5	2	7	2	7	0	1
8	F	A,B	4	2	6	5	9	3	0
9	G	C,D	2	8	10	11	13	3	0
10	H	D,E	4	8	12	9	13	1	0
11	I	E	6	7	13	7	13	0	1
12	J	E,F	4	7	11	9	13	2	0
13				D_p =	13		13		A-E-I

CPA-Gantt | CPA-Gantt (formulae) | Crashing | ··· | +

Figure 3. Project description and CPA results (duration in weeks).

	B	C	D	E	F	G	H	I	J
1									
2	Activity i ($i = 1, \ldots, n$)	Immediate Predecessors (FS)	Normal Duration d_i	Earliest Start j_i	Earliest Finish k_i	Latest Start l_i	Latest Finish m_i	Total Slack s_i	Critical Path ($i_c = 1$, $i_{nc} = 0$)
3	A	---	2	0	=E3+D3	=H3-D3	=MIN(G5;G6;G7;G8)	=H3-F3	=IF(I3=0;"1";"0")
4	B	---	2	0	=E4+D4	=H4-D4	=G8	=H4-F4	=IF(I4=0;"1";"0")
5	C	A	3	=F3	=E5+D5	=H5-D5	=G9	=H5-F5	=IF(I5=0;"1";"0")
6	D	A	6	=F3	=E6+D6	=H6-D6	=MIN(G9:G10)	=H6-F6	=IF(I6=0;"1";"0")
7	E	A	5	=F3	=E7+D7	=H7-D7	=MIN(G10;G11;G12)	=H7-F7	=IF(I7=0;"1";"0")
8	F	A,B	4	=MAX(F3:F4)	=E8+D8	=H8-D8	=G12	=H8-F8	=IF(I8=0;"1";"0")
9	G	C,D	2	=MAX(F5:F6)	=E9+D9	=H9-D9	=F13	=H9-F9	=IF(I9=0;"1";"0")
10	H	D,E	4	=MAX(F6:F7)	=E10+D10	=H10-D10	=F13	=H10-F10	=IF(I10=0;"1";"0")
11	I	E	6	=F7	=E11+D11	=H11-D11	=F13	=H11-F11	=IF(I11=0;"1";"0")
12	J	E,F	4	=MAX(F7:F8)	=E12+D12	=H12-D12	=F13	=H12-F12	=IF(I12=0;"1";"0")
13				D_p =	=MAX(F3:F12)		=MAX(H3:H12)		A-E-I

CPA-Gantt | CPA-Gantt (formulae) | Crashing | Crashing ··· | +

Figure 4. Project description and CPA results (formulae).

The Gantt (bar) chart of the project is shown in **Figure 5**. The bars with a purely dark color (A, E, I) represent the critical activities, while the two-colored bars (B, C, D, F, G, H, J) constitute the non-critical activities of the project (with their total slack in light gray, in accordance with column 8 in **Figure 3**). For example, activity C has a duration of 3 weeks (dark color) and a total slack of 6 weeks (light color). This means that the completion of the activity can be delayed until the exhaustion of the total float of 6 weeks, without increasing the total duration of the project.

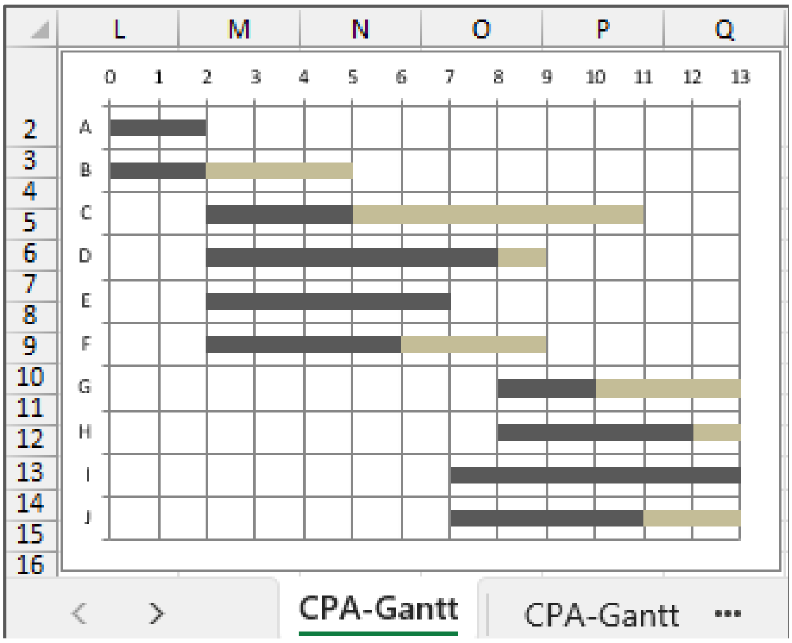

Figure 5. Gantt chart with critical (A, E, I) and non-critical (B, C, D, F, G, H, J) activities.

The AoN project network diagram usually provides a more transparent representation of the precedence connections between activities, as can be seen in **Figure 6**. The project critical path A–E–I is indicated with red arrows. It should be noted that a beginning dummy activity S and a terminal dummy activity K, both with a zero duration, were added to the analysis for network construction reasons.

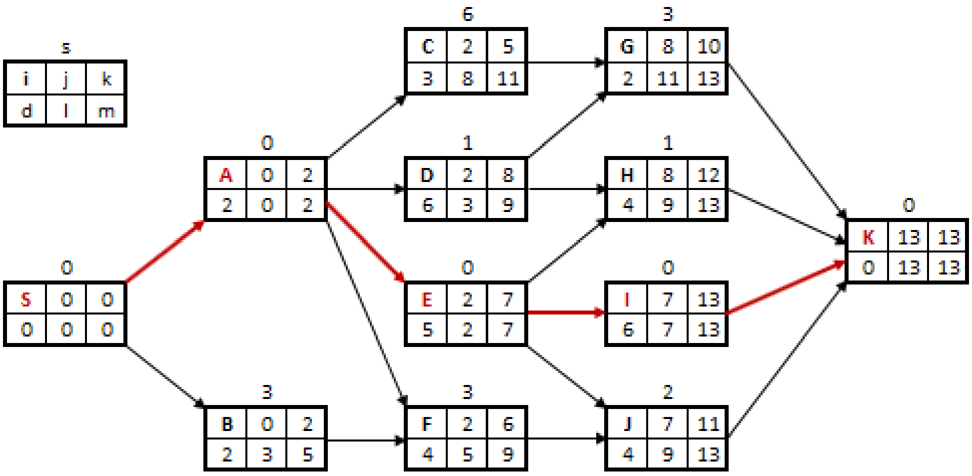

Figure 6. AoN project network with critical (A, E, I) and non-critical (B, C, D, F, G, H, J) activities.

Construction managers usually aim to find the optimal schedule or otherwise to identify the duration of the project that corresponds to the lowest total cost. They also want to know the minimum possible duration of project completion when accelerating the project. The required crashing duration and cost information for the project activities are presented in **Figure 7**. The total direct cost of the project (N_p) amounts to 615,000 EUR. Like the normal time estimates (**Figure 3**) the activity normal and crash cost estimates, as well as crash duration estimates in **Figure 7**, are also based on Monte Carlo simulations using historically relevant data from similar projects delivered by the same building contractor. **Figure 8** presents the formulae used to arrive at the information provided in **Figure 7**.

	B	C	D	E	F	G	H
1							
2	Activity i (i = 1, ..., n)	Normal Duration d_i	Normal Cost N_i	Crash Duration t_i	Crash Cost C_i	max Time Reduction r_i	Marginal Crash Cost A_i
3	A	2	60000	2	---	---	---
4	B	2	30000	1	20000	1	20000
5	C	3	60000	2	20000	1	20000
6	D	6	60000	4	30000	2	15000
7	E	5	75000	3	30000	2	15000
8	F	4	60000	3	20000	1	20000
9	G	2	30000	1	20000	1	20000
10	H	4	60000	3	12000	1	12000
11	I	6	120000	4	20000	2	10000
12	J	4	60000	3	12000	1	12000
13		N_p =	615000				

Crashing | Crashing (formulae)

Figure 7. Project crashing information (cost in EUR).

	B	C	D	E	F	G	H
1							
2	Activity i (i = 1, ..., n)	Normal Duration d_i	Normal Cost N_i	Crash Duration t_i	Crash Cost C_i	max Time Reduction r_i	Marginal Crash Cost A_i
3	A	2	60000	2	---	---	---
4	B	2	30000	1	20000	=C4-E4	=F4/G4
5	C	3	60000	2	20000	=C5-E5	=F5/G5
6	D	6	60000	4	30000	=C6-E6	=F6/G6
7	E	5	75000	3	30000	=C7-E7	=F7/G7
8	F	4	60000	3	20000	=C8-E8	=F8/G8
9	G	2	30000	1	20000	=C9-E9	=F9/G9
10	H	4	60000	3	12000	=C10-E10	=F10/G10
11	I	6	120000	4	20000	=C11-E11	=F11/G11
12	J	4	60000	3	12000	=C12-E12	=F12/G12
13		N_p =	=SUM(D3:D12)				

Crashing | Crashing (formulae) | Duration

Figure 8. Project crashing information (formulae).

The project planners are in search of both the most economical and the fastest combination of activities to execute. In addition, they are interested in performing quick "what-if" analyses to obtain useful information in cases when discrepancies between the construction schedule and the actual execution progress arise [73]. The significant possibilities offered by spreadsheet modelling in solving the TCTP and in performing fast investigations by construction managers are examined throughout this section.

The spreadsheet-based model development of the specific project's TCTP using appropriate formulae can be seen in **Figure 9**. Columns from B to E correspond to the Nodes part of the AoN project network of **Figure 6**, containing the project activities i (B4:B14) and their normal duration d_i (C4:C14), earliest starting times b_i (D4:D14), and crashing times w_i (E4:E14), i.e., the amount by which each activity is crashed. Columns from G to J constitute the Arcs (arrows) part of the model. Columns G and H contain each pair of connected activities from their start node (G4:G19) to their finish node (H4:H19) according to the project definition (**Figure 3**). Columns I and J represent the LHS and the RHS of the precedence connections constraint (14) in the LP formulation, respectively, i.e., the real time between arcs and the minimum time between arcs. For instance, from activity A (cell G4) to activity C (cell H4), the formula in cell I4 is:

= VLOOKUP (H4;$B$4:$D$14;3) – VLOOKUP (G4;$B$4:$D$14;3) (18)

	B	C	D	E	G	H	I	J	L	M
1										
2		Nodes	b_i	w_i	Arcs		LHS	RHS	r_i	A_i
3	Activity i	Normal Duration d_i	Start Time	Crash Time	From	To	Real Time between Arcs	min Time between Arcs	max Crash Time	Marginal Crash Cost
4	A	2	0	0	A	C	=VLOOKUP(H4;$B$4:$D$14;3)-VLOOKUP(G4;$B$4:$D$14;3)	=VLOOKUP(G4;$B$4:$C$14;2)-VLOOKUP(G4;$B$4:$E$14;4)	0	0
5	B	2	0	0	A	D	=VLOOKUP(H5;$B$4:$D$14;3)-VLOOKUP(G5;$B$4:$D$14;3)	=VLOOKUP(G5;$B$4:$C$14;2)-VLOOKUP(G5;$B$4:$E$14;4)	1	20000
6	C	3	6	0	A	E	=VLOOKUP(H6;$B$4:$D$14;3)-VLOOKUP(G6;$B$4:$D$14;3)	=VLOOKUP(G6;$B$4:$C$14;2)-VLOOKUP(G6;$B$4:$E$14;4)	1	20000
7	D	6	3	0	A	F	=VLOOKUP(H7;$B$4:$D$14;3)-VLOOKUP(G7;$B$4:$D$14;3)	=VLOOKUP(G7;$B$4:$C$14;2)-VLOOKUP(G7;$B$4:$E$14;4)	2	15000
8	E	5	2	0	B	F	=VLOOKUP(H8;$B$4:$D$14;3)-VLOOKUP(G8;$B$4:$D$14;3)	=VLOOKUP(G8;$B$4:$C$14;2)-VLOOKUP(G8;$B$4:$E$14;4)	2	15000
9	F	4	5	0	C	G	=VLOOKUP(H9;$B$4:$D$14;3)-VLOOKUP(G9;$B$4:$D$14;3)	=VLOOKUP(G9;$B$4:$C$14;2)-VLOOKUP(G9;$B$4:$E$14;4)	1	20000
10	G	2	9	0	D	G	=VLOOKUP(H10;$B$4:$D$14;3)-VLOOKUP(G10;$B$4:$D$14;3)	=VLOOKUP(G10;$B$4:$C$14;2)-VLOOKUP(G10;$B$4:$E$14;4)	1	20000
11	H	4	9	0	D	H	=VLOOKUP(H11;$B$4:$D$14;3)-VLOOKUP(G11;$B$4:$D$14;3)	=VLOOKUP(G11;$B$4:$C$14;2)-VLOOKUP(G11;$B$4:$E$14;4)	1	12000
12	I	6	7	0	E	H	=VLOOKUP(H12;$B$4:$D$14;3)-VLOOKUP(G12;$B$4:$D$14;3)	=VLOOKUP(G12;$B$4:$C$14;2)-VLOOKUP(G12;$B$4:$E$14;4)	2	10000
13	J	4	9	0	E	I	=VLOOKUP(H13;$B$4:$D$14;3)-VLOOKUP(G13;$B$4:$D$14;3)	=VLOOKUP(G13;$B$4:$C$14;2)-VLOOKUP(G13;$B$4:$E$14;4)	1	12000
14	K	0	13	0	E	J	=VLOOKUP(H14;$B$4:$D$14;3)-VLOOKUP(G14;$B$4:$D$14;3)	=VLOOKUP(G14;$B$4:$C$14;2)-VLOOKUP(G14;$B$4:$E$14;4)	0	0
15					F	J	=VLOOKUP(H15;$B$4:$D$14;3)-VLOOKUP(G15;$B$4:$D$14;3)	=VLOOKUP(G15;$B$4:$C$14;2)-VLOOKUP(G15;$B$4:$E$14;4)		
16	D_p =	=D14+C14-E14	T_p =	13	G	K	=VLOOKUP(H16;$B$4:$D$14;3)-VLOOKUP(G16;$B$4:$D$14;3)	=VLOOKUP(G16;$B$4:$C$14;2)-VLOOKUP(G16;$B$4:$E$14;4)	C_p =	=SUMPRODUCT(E4:E14;M4:M14)
17					H	K	=VLOOKUP(H17;$B$4:$D$14;3)-VLOOKUP(G17;$B$4:$D$14;3)	=VLOOKUP(G17;$B$4:$C$14;2)-VLOOKUP(G17;$B$4:$E$14;4)		
18	O_t =	25000	O_p =	=C18*C16	I	K	=VLOOKUP(H18;$B$4:$D$14;3)-VLOOKUP(G18;$B$4:$D$14;3)	=VLOOKUP(G18;$B$4:$C$14;2)-VLOOKUP(G18;$B$4:$E$14;4)	B_p =	=Crashing!D13+M16+E18
19					J	K	=VLOOKUP(H19;$B$4:$D$14;3)-VLOOKUP(G19;$B$4:$D$14;3)	=VLOOKUP(G19;$B$4:$C$14;2)-VLOOKUP(G19;$B$4:$E$14;4)		

Figure 9. Basic LP model development in a spreadsheet (formulae).

The first VLOOKUP function in Formula (18) searches for the letter (activity) C (cell H4) in the first column of the range $B$4:$D$14 (the dollar symbol is used to facilitate copy and paste functions from I4 to I5:I19), finds C in cell B6, and then returns the matching value 6 from the third column of the range (cell D6). Similarly, the second VLOOKUP function searches for the letter (activity) A (cell G4) in the first column of the above range, matches A in cell B4, and returns zero from the third column of that range (cell D4). The difference between these values (6 − 0 = 6) represents the amount of time between the starting times of activities A and C (LHS). The corresponding RHS values are calculated in column J. For instance, the formula in cell J4 is:

$$= \text{VLOOKUP (G4;\$B\$4:\$C\$14;2)} - \text{VLOOKUP (G4;\$B\$4:\$E\$14;4)} \tag{19}$$

Now, the first VLOOKUP function in Formula (19) searches for the letter (activity) A (cell G4) in the first column of the range $B$4:$C$14 (the dollar symbol is again used to facilitate copy and paste functions of J4 to J5:J19), finds A in cell B4, and then returns the matching value 2 (the normal duration of activity A) from the second column of the range (cell C4). In a similar way, the second VLOOKUP function searches for the letter (activity) A (cell G4) in the first column of the same range, matches A in cell B4, and returns the amount of crash time from the fourth column of the range (cell E4). The difference between these values (2 − 0 = 2) represents the minimum duration of activity after crashing (RHS).

The formula for the Objective function to minimize project duration (Duration Model) is inserted in cell C16:

$$= \text{D14} + \text{C14} - \text{E14} \tag{20}$$

The resulting value is the completion time of the project which coincides with the finish time of the dummy terminal activity K. The formula for the Objective function to minimize the total additional cost for crashing the project (Cost Model) is entered into cell M16:

$$= \text{SUMPRODUCT(E4:E14;M4:M14)} \tag{21}$$

This formula calculates the sum of the products between the (marginal) crash cost per week for each activity (M4:M14) and the amount by which each activity is crashed (E4:E14). Cell C18 contains the weekly indirect cost of the project (O_t), which is set to the fixed amount of 25,000 EUR. The total indirect project cost (O_p) is calculated in cell E18 (=C18*C16). Finally, in cell M18, the total project cost (B_p) is calculated (as the sum of total normal direct cost, total indirect cost, and total cost for project crashing). Cells C18, E18, and M18 are used in the optimization of the modified version of the LP model. The basic normal execution calculated values for duration and cost parameters of the problem can be seen in **Figure 10**.

Once all required data have been entered into the spreadsheet and the validity of the LP model has been confirmed, three options must be defined for using the solver optimization add-in tool: i) the "objective function" cell containing the mathematical formula to be optimized (in all three cases, to minimize project duration and costs), ii) the "decision variables" cells containing the TCTP significant scheduling variables (the start and crash times for project activities), the values of which are changing each time a new solution to the problem is generated, and iii) the "constraints" cells containing the technological restrictions applied to the specific project, i.e., the precedence relationships between activities in the network, and their maximum feasible crash times. In order to ensure that all required linearity conditions are met in the LP model so that the Simplex LP solving method can be used to produce global optimal results, a dummy terminal activity (activity K) is added to the problem (with zero duration) which is directly connected (with FS precedence relation with no leads/lags) to the activities G, H, I, and J.

The Duration Model requires 22 decision variables and 38 constraints (**Figure 11**). Cell C16 (the project duration D_p to be minimized) is inserted in the Set Objective field. Cell range D4:E14 is selected in the Changing Variable Cells field (start times b_i and crash times w_i). In the Constraints field, the following information is added: D4:E14 ≥ 0 (non-negative variable cells); E4:E14 ≤ L4:L14 (maximum restriction for crash times); and I4:I19 ≥ J4:J19 (precedence relationships between activities or else LHS ≥ RHS).

Based on the results from the application of the Duration Model, the shortest technologically feasible implementation duration of the project is 9 weeks (**Figure 12**). However, it should be noted that the total crash cost of 112,000 EUR is not *per se* the minimum crash cost since this version of the LP model has set as the objective function the time parameter (not the cost parameter). Therefore, other optimal solutions may arise, i.e., different project schedules which will allow the minimum project completion time to be 9 weeks but at a lower crashing cost C_p. To test whether this result is truly the minimum project crash cost, the Cost Model described earlier can now be applied, whereas the target is to minimize the crash cost by holding the project duration at 9 weeks (**Figure 13**). Thus, cell M16 is replacing cell C16, and the constraint C16 <= E16 is added ($D_p <= T_p$). Indeed, the new solution reveals that the total cost for accelerating the project is 8,000 EUR less, i.e., 104,000 EUR (**Figure 14**). Considering that the Simplex LP solving method is used, this value represents the global optimal minimum crash cost. The activities that need to be crashed are D, E, H, I and J by 2, 2, 1, 2 and 1 weeks, respectively. The Cost Model involves 22 decision variables and 39 constraints.

	B	C	D	E	F	G	H	I	J	K	L	M
1												
2	Nodes		b_i	w_i		Arcs		LHS	RHS		r_i	A_i
3	Activity i	Normal Duration d_i	Start Time	Crash Time		From	To	Real Time between Arcs	min Time between Arcs		max Crash Time	Marginal Crash Cost
4	A	2	0	0		A	C	6	2		0	0
5	B	2	0	0		A	D	3	2		1	20000
6	C	3	6	0		A	E	2	2		1	20000
7	D	6	3	0		A	F	5	2		2	15000
8	E	5	2	0		B	F	5	2		2	15000
9	F	4	5	0		C	G	3	3		1	20000
10	G	2	9	0		D	G	6	6		1	20000
11	H	4	9	0		D	H	6	6		1	12000
12	I	6	7	0		E	H	7	5		2	10000
13	J	4	9	0		E	I	5	5		1	12000
14	K	0	13	0		E	J	7	5		0	0
15						F	J	4	4			
16	D_p =	13	T_p =	13		G	K	4	2		C_p =	0
17						H	K	4	4			
18	O_t =	25000	O_p =	325000		I	K	6	6		B_p =	940000
19						J	K	4	4			

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Figure 10. Basic LP model (no crashing, parameter values for normal durations, D_p = 13 weeks).

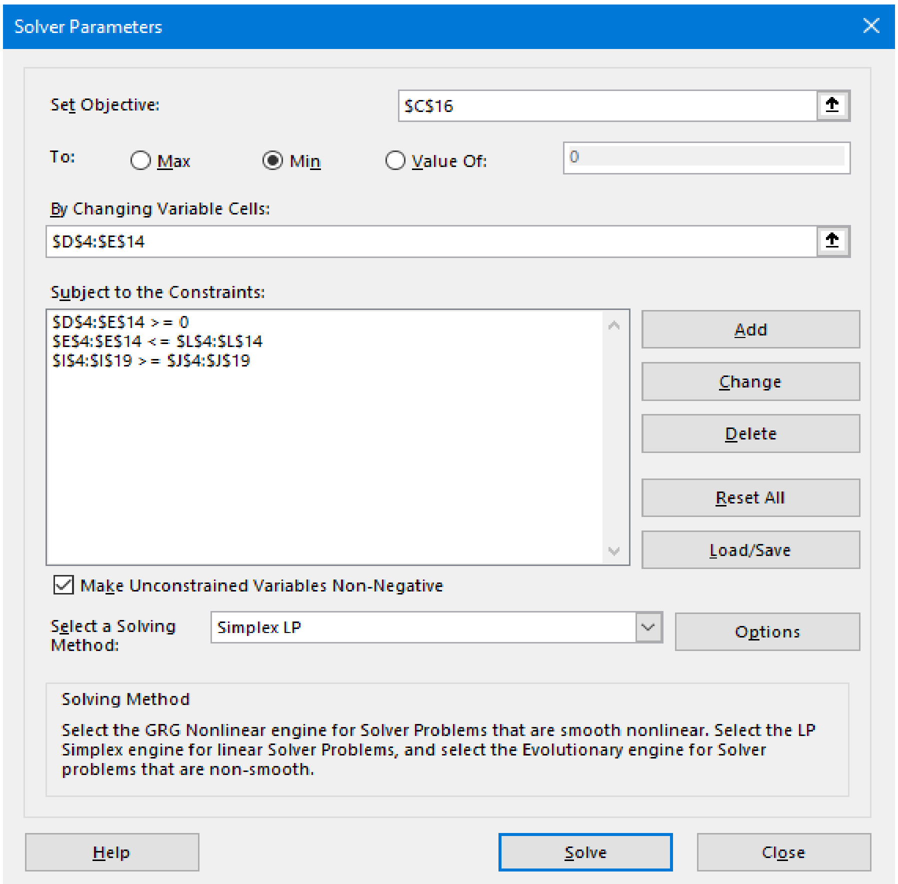
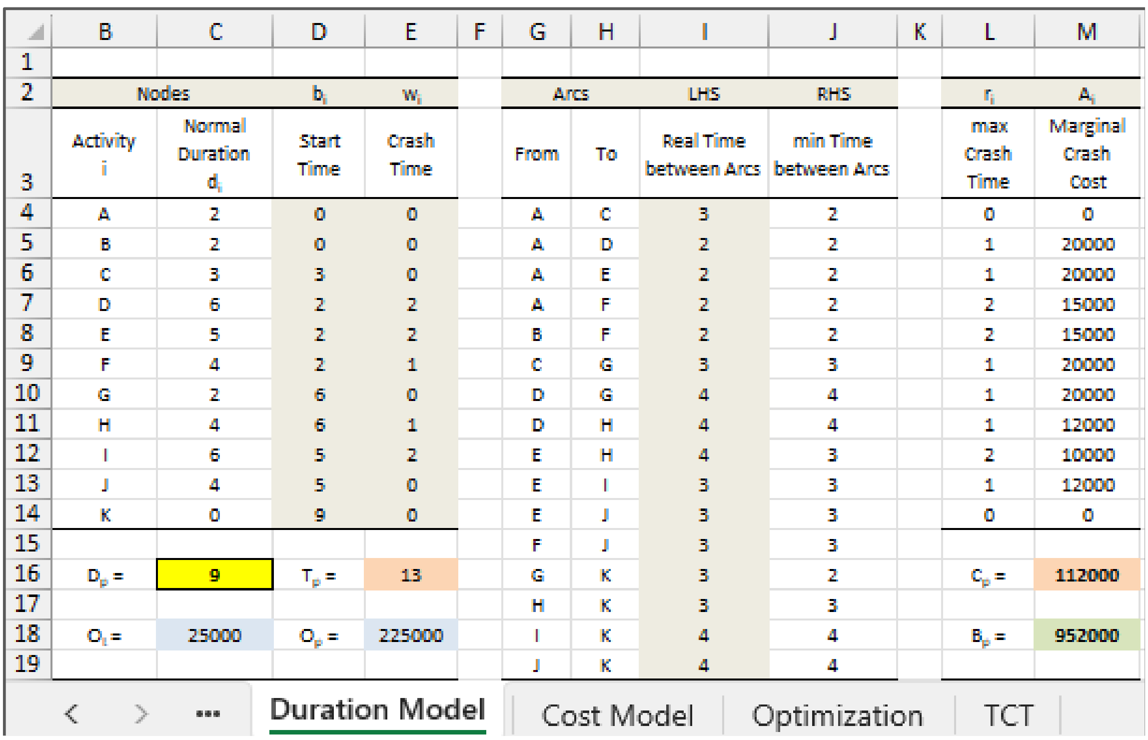


Figure 11. Solver dialog box for Duration Model.



	B	C	D	E	F	G	H	I	J	K	L	M
1												
2	Nodes		b_i	w_i		Arcs		LHS	RHS		r_i	A_i
3	Activity i	Normal Duration d_i	Start Time	Crash Time		From	To	Real Time between Arcs	min Time between Arcs		max Crash Time	Marginal Crash Cost
4	A	2	0	0		A	C	3	2		0	0
5	B	2	0	0		A	D	2	2		1	20000
6	C	3	3	0		A	E	2	2		1	20000
7	D	6	2	2		A	F	2	2		2	15000
8	E	5	2	2		B	F	2	2		2	15000
9	F	4	2	1		C	G	3	3		1	20000
10	G	2	6	0		D	G	4	4		1	20000
11	H	4	6	1		D	H	4	4		1	12000
12	I	6	5	2		E	H	4	3		2	10000
13	J	4	5	0		E	I	3	3		1	12000
14	K	0	9	0		E	J	3	3		0	0
15						F	J	3	3			
16	D_p =	9	T_p =	13		G	K	3	2		C_p =	112000
17						H	K	3	3			
18	O_i =	25000	O_p =	225000		I	K	4	4		B_p =	952000
19						J	K	4	4			

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Figure 12. Results from Duration Model (minimum project duration: $D_p = 9$ weeks).

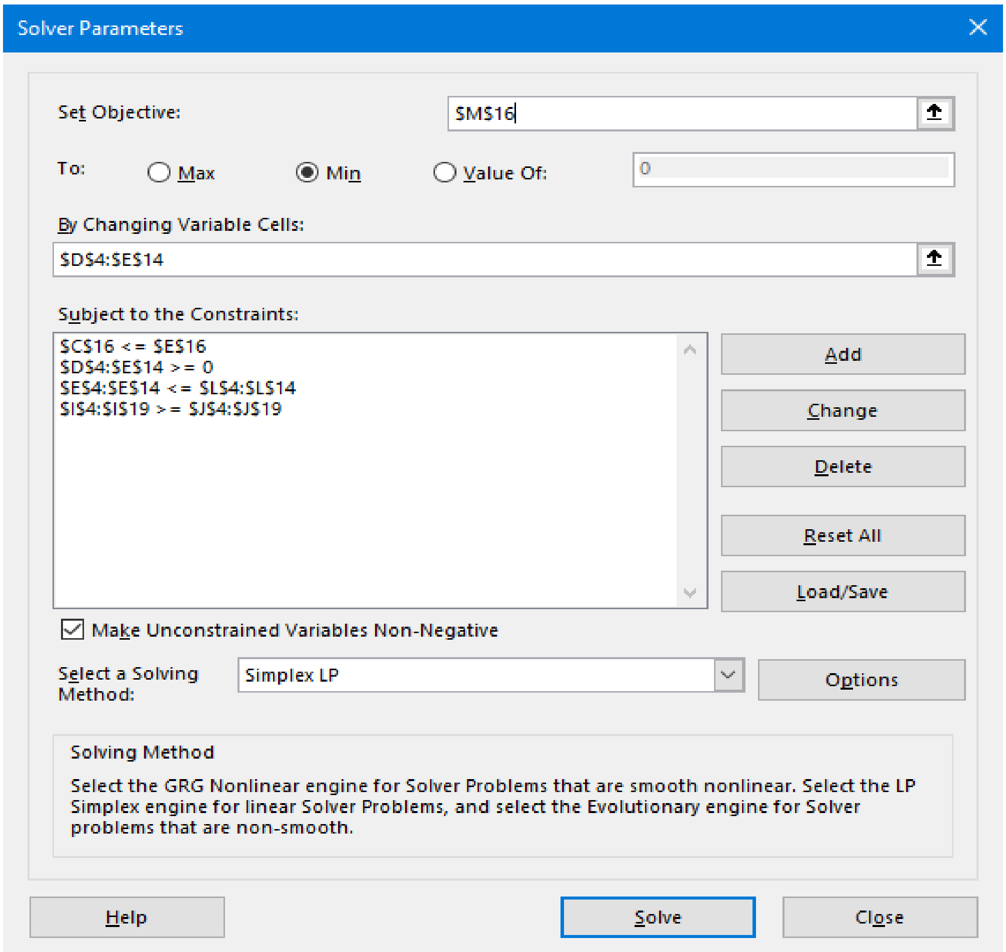
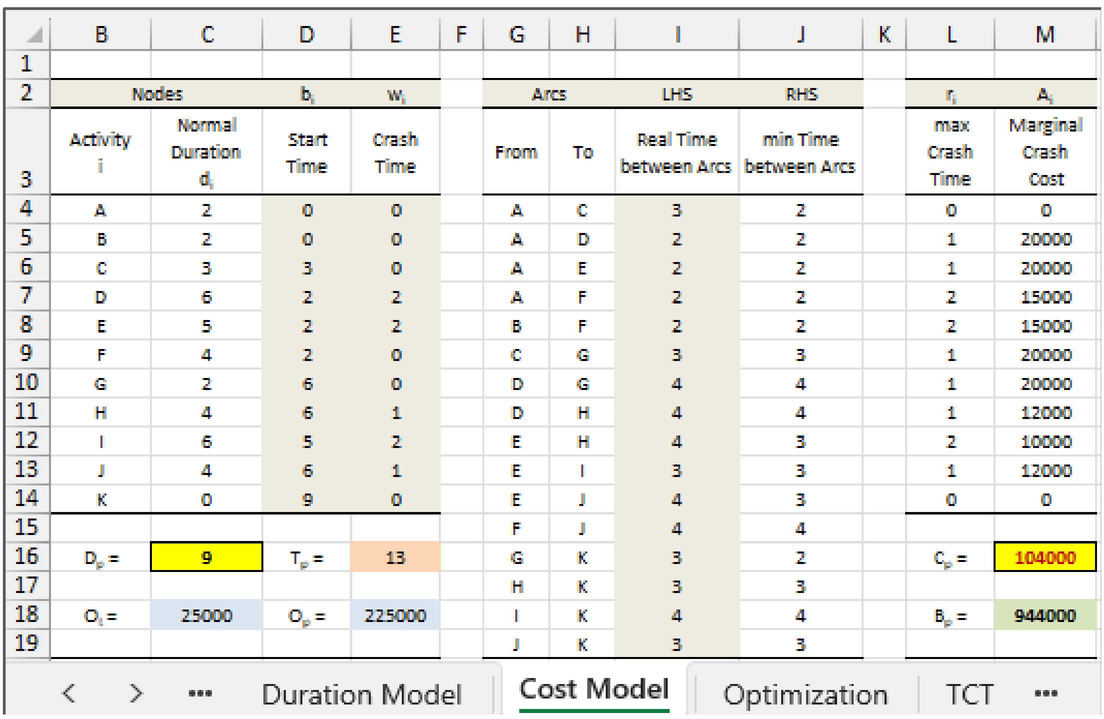


Figure 13. Solver dialog box for Cost Model.



	B	C	D	E	F	G	H	I	J	K	L	M
1												
2	Nodes		b_i	w_i		Arcs		LHS	RHS		r_i	A_i
3	Activity i	Normal Duration d_i	Start Time	Crash Time		From	To	Real Time between Arcs	min Time between Arcs		max Crash Time	Marginal Crash Cost
4	A	2	0	0		A	C	3	2		0	0
5	B	2	0	0		A	D	2	2		1	20000
6	C	3	3	0		A	E	2	2		1	20000
7	D	6	2	2		A	F	2	2		2	15000
8	E	5	2	2		B	F	2	2		2	15000
9	F	4	2	0		C	G	3	3		1	20000
10	G	2	6	0		D	G	4	4		1	20000
11	H	4	6	1		D	H	4	4		1	12000
12	I	6	5	2		E	H	4	3		2	10000
13	J	4	6	1		E	I	3	3		1	12000
14	K	0	9	0		E	J	4	3		0	0
15						F	J	4	4			
16	D_p =	9	T_p =	13		G	K	3	2		C_p =	104000
17						H	K	3	3			
18	O_I =	25000	O_p =	225000		I	K	4	4		B_p =	944000
19						J	K	3	3			

Figure 14. Results from Cost Model (minimum total crash cost: C_p = 104,000 EUR).

Figure 15 shows the Solver inputs for the solution to the problem of identifying the optimal relationship between the duration and the total cost of the project (Optimization Model). In cell M18, the objective function is minimized, namely the project total cost (B_p), which results in 922,000 EUR (**Figure 16**). The corresponding project duration is 11 weeks (cell C16). The minimum total cost is the sum of the normal cost (615,000 EUR), the indirect cost (275,000 EUR), and the additional cost for crashing activities (32,000 EUR). The critical activities whose execution must be accelerated by 1 week (cell E11) and 2 weeks (cell E12), respectively, are H and I, which are also the most economical selection considering the marginal (weekly) compression cost (cells M11 and M12). For the implementation of the Optimization Model, 22 decision variables and 38 constraints are required (same as for the Duration Model).

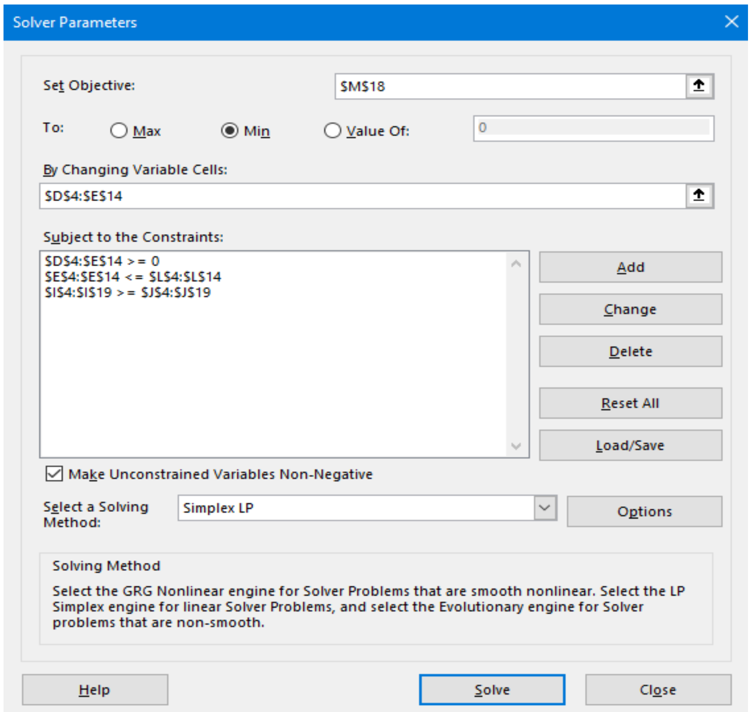


Figure 15. Solver dialog box for Optimization Model.

	B	C	D	E	F	G	H	I	J	K	L	M
1												
2	Nodes		b_i	w_i		Arcs		LHS	RHS		r_i	A_i
3	Activity i	Normal Duration d_i	Start Time	Crash Time		From	To	Real Time between Arcs	min Time between Arcs		max Crash Time	Marginal Crash Cost
4	A	2	0	0		A	C	5	2		0	0
5	B	2	0	0		A	D	2	2		1	20000
6	C	3	5	0		A	E	2	2		1	20000
7	D	6	2	0		A	F	3	2		2	15000
8	E	5	2	0		B	F	3	2		2	15000
9	F	4	3	0		C	G	3	3		1	20000
10	G	2	8	0		D	G	6	6		1	20000
11	H	4	8	1		D	H	6	6		1	12000
12	I	6	7	2		E	H	6	5		2	10000
13	J	4	7	0		E	I	5	5		1	12000
14	K	0	11	0		E	J	5	5		0	0
15						F	J	4	4			
16	D_p =	11	T_p =	13		G	K	3	2		C_p =	32000
17						H	K	3	3			
18	O_i =	25000	O_p =	275000		I	K	4	4		B_p =	922000
19						J	K	4	4			

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Figure 16. Results from Optimization Model (minimum project total cost: B_p = 922,000 EUR).

For the verification of the above third optimization version of the herein proposed threefold LP model, the Duration Model can be solved five times, each time for a different set duration. Starting from the standard (normal) duration of 13 weeks (zero crashing), the model is solved separately for the specified durations of 12, 11, 10 and 9 weeks. The results from the obtained solutions for the significant parameters of the TCTP are summarized in **Table 1**. Obviously, the optimal duration-cost combination for the project is (D_p, B_p) = (11 weeks, 922,000 EUR).

Table 1. Project crashing results (cost in EUR).

D_p	C_p	N_p	O_p	B_p
9	104,000	615,000	225,000	944,000
10	62,000	615,000	250,000	927,000
11	32,000	615,000	275,000	922,000
12	10,000	615,000	300,000	925,000
13	0	615,000	325,000	940,000

Finally, relevant graphs of the trade-off relationships between project duration and: i) crash cost C_p (**Figure 17**), ii) indirect cost O_p (**Figure 18**), and iii) total cost B_p (**Figure 19**), from the different solutions of the LP spreadsheet-based model with Solver, are aligned and depicted below.

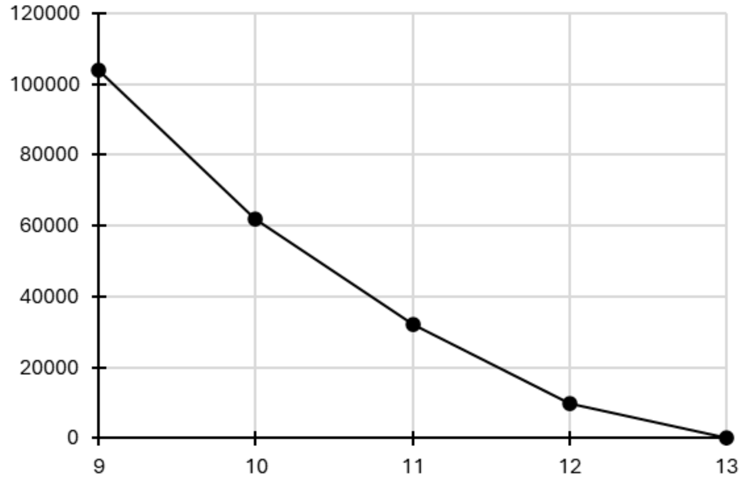

Figure 17. Duration vs. Crash Cost (minimum duration: 9 weeks).

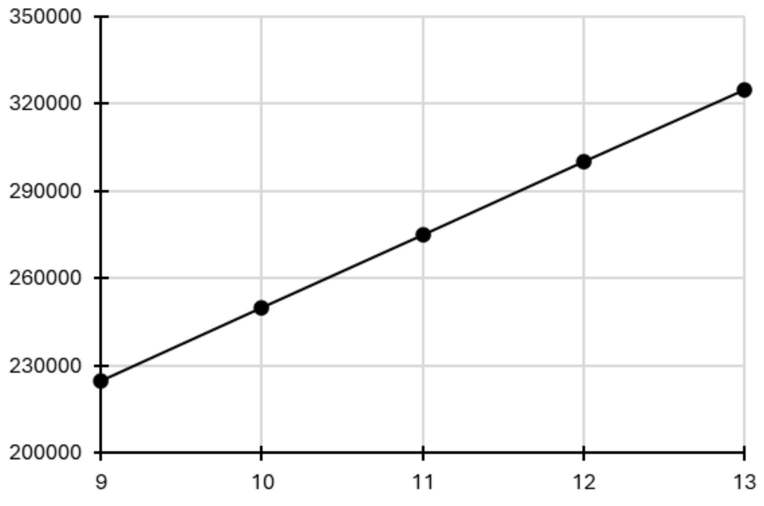

Figure 18. Duration vs. Indirect Cost.

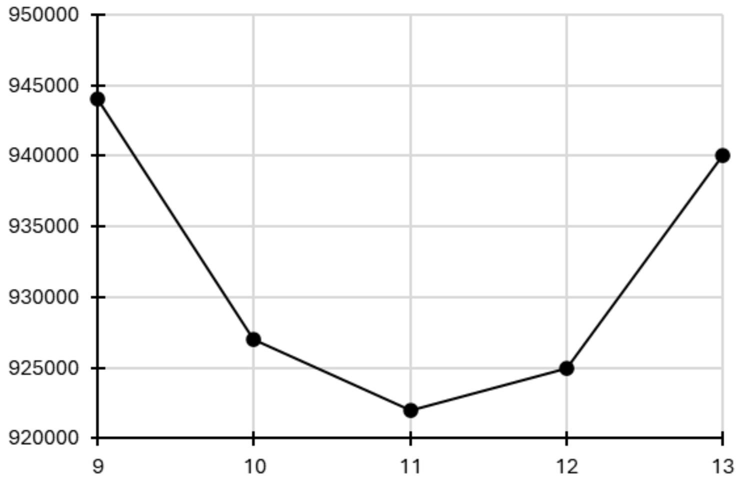

Figure 19. Duration vs. Total Cost Relationship (optimal duration: 11 weeks).

Following these results, if management decides to complete the project as soon as possible, in case there is a bonus to be earned or to free-up resources for transferring to parallel projects, then activities A, B, C, D, E, F, G, H, I and J should take 2, 2, 3, 4, 3, 4, 2, 3, 4, and 3 weeks, respectively. This strategy will allow construction managers to complete the project in 9 weeks at an additional accelerating cost of 104,000 EUR, an indirect cost of 225,000 EUR, and a total cost of 944,000 EUR. Assuming that the optimal point of time-cost trade-off is decided to be followed, then activities A, B, C, D, E, F, G, H, I and J must be executed at 2, 2, 3, 6, 5, 4, 2, 3, 4, and 4 weeks, respectively. With this strategy, the project will be finished in 11 weeks with an additional duration shortening cost of 32,000 EUR, an indirect cost of 275,000 EUR, and a total cost of 922,000 EUR. Obviously, any change in any of the values of the time-cost variables of the problem implies automatic proportional changes in the solution results.

4. Conclusions

Project managers want to have immediate results based on different feasible time-cost combinations for the implementation of activities. Therefore, this paper presents a practical project management scheduling method that can be easily and at relatively low cost implemented in a spreadsheet. The additional optimization solution tool integrated into spreadsheets, which is freely available, allows users to very quickly identify optimal solutions that, in the time-cost management of a project, translate into either the most economical or the shortest possible schedule that simultaneously cover all the requirements of the project owner in terms of technical, financial and other specifications.

For reasons of easier understanding of the above technique, a relatively narrowly defined project was chosen in this work, although there is the possibility of solving problems in much larger projects, which may require up to thousands of constraints and/or variables. In addition to the clear display of the results in the spreadsheet where the basic LP model is developed, the use of the additional solution tool allows the execution of an unlimited number of simulations by changing the values of the different parameters of the project problem (e.g., normal durations, time compression costs, precedence relationships between activities, etc.) and checking the resulting schedule each time. This functionality is highly desirable in project management in general and especially in projects that are planned to be implemented in a dynamic and unpredictable environment like construction. In cases of recording deviations between the planned and the actual progress of the project, it is necessary to immediately adapt the schedule to these changes and to estimate the consequent future impacts on the project performance.

In conclusion, one could argue that spreadsheets in combination with the add-in mathematical problem-solving algorithms can be a useful and easy-to-implement simulation and optimization tool that could contribute to more effective decision-making in construction project management. The ability of the methodology proposed in this paper to answer a significant number of critical questions during the design, planning and execution phases of projects is a fact that should encourage both academic tutors and practitioners to adopt its systematic application in the teaching and practical implementation of construction project management, respectively.

This paper dealt specifically with deterministic linear time-cost optimization problems in construction management. In addition, only the immediate finish-to-start precedence connection between activities was considered. Future work will address the often more demanding discrete time-cost relationship, the probabilistic version of the TCTP, whereas frequency distribution functions are assigned to both normal and crash durations and costs, and different types of activity precedence constraints with leads and/or lags.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Research data are available upon request.

Acknowledgments

The author is sincerely grateful to the two anonymous reviewers for their constructive comments towards the improvement of the paper.

Conflicts of Interest

The author declares no conflict of interest.

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