# SIXTY YEARS OF PROJECT PLANNING: HISTORY AND FUTURE

Keynote Lecture

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## Abstract

Modern project management owes its reputation to the development of modern scheduling techniques based on the theory of graphs, namely network scheduling techniques. In 2017, these techniques are celebrating their sixtieth birthday. This anniversary provides the opportunity to look back at the most important achievements such as non-linear activities and new precedence relations, and to take a look into the future. The highlights of this subjective retrospective are the presentation of the latest results and the compilation of those problems that will probably define the priorities for future research.

## Keywords

Network scheduling; Critical Path Method; PERT; Precedence Diagramming Method; continuous precedence relations; non-linear activities; logical switches

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# 1 THE BEGINNINGS

The first appearance of modern planning techniques dates back to the Cold War and the time the first computers started to be used for such purposes. These techniques differ from traditional ones such as the Gantt chart or Linear Scheduling Method in that they allow the logic underlying the plan to be directly modelled. Modern techniques also make this logic graphically understandable and visible. These plans are depicted as graphs, where the sequence of the activities is shown as chains of vertices and arrows. Due to the aforementioned, modern techniques are often referred to as network techniques. Dozens of planning techniques have been developed, however all of them are based on either one of the first three techniques that were introduced: Program Evaluation and Review Technique (PERT), Critical Path Method (CPM) and Precedence Diagram Method (PDM). In the following sections, the history of these techniques will be briefly introduced.

## 1.1 The Program Evaluation and Review Technique (PERT)

In the highly tense atmosphere of the Cold War, the US Navy launched the POLARIS program, whose purpose was to develop a submarine-launched nuclear-armed ballistic missile. In the spring of 1956 Admiral Raborn, the "owner" of the Polaris program, ordered the Plans and Programs Division of the Special Projects Office (SPO) to do a research on the existing tools of project planning and management. Their work brought little success; therefore they started to develop their own method. In December 1956, a research team was formed of SPO, Booz, Allen & Hamilton consulting firm and the experts of the Lockheed Corporation. In January 1957, Raborn defined the most important expectations regarding the tracking of the project: "*I must be able to reach down to any level of Special Projects Office activity and find a plan and performance report that logically and clearly can be related to the total job, we have to do*." [1]. The team set the aims of the future system, and the research proceeded quickly. In October 1957, PERT was running on a computer, and according to the official statement they began to apply it for the project. However, PERT was not "really" applied on the POLARIS program [1]. No wonder – managing programs involving around 120 contractors and about thousands of subcontractors is even nowadays a challenging task for the best planners, who are equipped with the latest IT technology and computer application. Lacking an adequate methodology, and having to program with punched cards and with less than 10 KB memory, made PERT really hard to apply in large real-life projects. There is another argument explaining why PERT was not used at that time: the theoretical flaw in the method's rules for calculation, which will be discussed in Section 2. The popularization of PERT also started in these times, with the help of SPO's public relations machinery. The first scientific paper was published in 1959 [2]. By 1962, the US government alone had issued 139 documents about PERT. By 1964 the number of scientific announcements, books and reports on the technique had reached one thousand. The technique became so widespread that some authors use it as a synonym for network technique even today, and equate network diagrams with PERT diagrams, causing serious misunderstandings.

## 1.2 The Critical Path Method (CPM)

The development of the CPM technique started in 1956, when the management of DuPont decided to utilize their UNIVAC 1 computer (Fig. 1) to support the maintenance work of their production plants. The management of the company wanted to prove that IT is the future, and that the money they had spent on the computer was not in vain.


*Figure1: Mercury delay line memory of UNIVAC I ( https://en.wikipedia.org/wiki/UNIVAC_I)*

DuPont's management thought that using the computer for planning and cost optimization was an excellent way to prove its utility. Morgan Walker, an engineer at DuPont, got the assignment of figuring out whether UNIVAC could be used for solving such problems. There were also other researchers within DuPont investigating the same thing; however, none of them could come up with a useful solution. Between the second half of 1956 and the beginning of 1957, Morgan Walker and James E. Kelley from the Remington Rand research institute, who joined the project in the meantime, were able to define an existing project, whose logical dependencies they had discovered. On May 7, 1957, DuPont and Remington Rand officially created the CPM project, worth USD 226,400. DuPont's share was USD 167,700, while Remington Rand's was USD 58,700. The research was led by Morgan Walker on DuPont's side, who defined the problem, and the mathematician James E. Kelley on Remington Rand's side, whose job was to find the mathematical solution for the problem. Kelley transformed the problem into a parametric linear programming one, which he could solve. The first network prepared for tests were called Fisher's work and was ready for tests by 24 July 1957. The network consisted of 61 activities and 16 dummy activities. The result of the analysis, i.e. the least cost solutions for the given project durations, can be seen on Fig. 2, while Figure 3 shows a drawing explaining the algorithm.

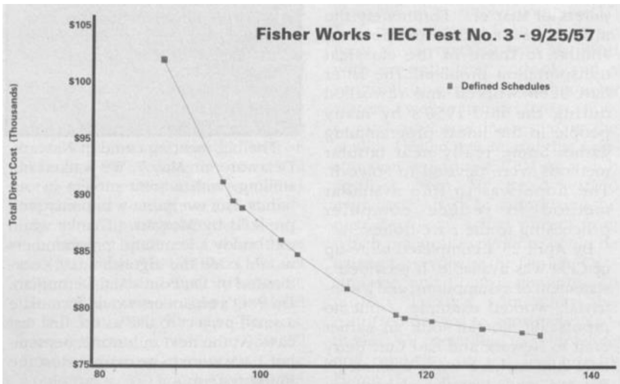



*Fig. 2: Result of the first CPM analysis made by computer [3]*

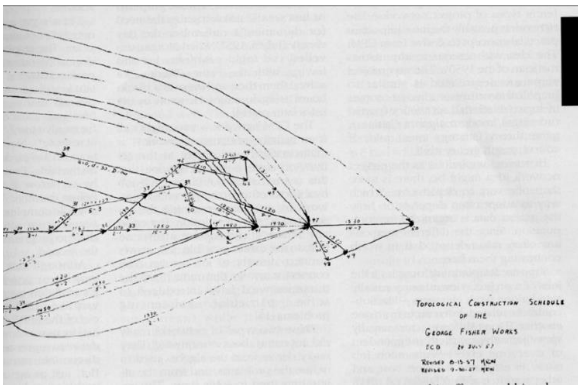



*Fig. 3: Topology graph of the CPM network [3]*

The first scientific paper on the CPM technique was published in 1959 [4], and another one in 1961 [5]. Popularization of the CPM in the construction industry is due to the work of Fondahl [6].

### 1.3 The Precedence Diagramming Method (PDM)

The PERT and the CPM, the two techniques most connected to the beginnings of project management, have lost their significance over the decades. Despite thousands of papers published on PERT each year, it has not been improved sufficiently to be widely used by project managers. The original CPM network planning technique has suffered a similar fate. Both the mathematical apparatus needed for the solution and the necessary computers were unavailable for the masses. Therefore, the CPM technique was simplified over time. It was used for time analysis instead of cost optimization. However, there were other problems as well, which made the application of even this simplified technique difficult. The most important one of these was how to draw the CPM network based on the list of activities and on the list of immediate predecessors. John Fondahl, a pioneer of network techniques, has noticed that drawing a CPM network was a very daunting task, especially in case of bigger projects [6]. It is now known that drawing a CPM (activity-on-arrow) network with the minimal number of dummies is an NP hard problem [7]. To avoid this problem, Fondahl recommended a new way of drawing the network, the activity-on-node notation. His suggestion is an important prelude to the PDM planning technique. According to his reminiscences [8], the first three precedence relations – the Start-to-Start (SS), the Finish-to-Start (FS) and the Finish-to-Finish (FF) – had appeared in an IBM application in 1964 [9]. The term Precedence Diagramming Method also came from the IBM team [8]. Researches regarding network scheduling had also taken place in Europe. The most notable and significant among these was the development of the so-called Metra Potential Method (MPM), which was developed by Roy [10, 11]. His MPM network was an activity-on-node network that utilized the Start-to-Start relations with minimal and maximal lags. In this sense, it was more advanced than the PDM. The two techniques were practically the same, and it is important to note that Fondahl and Roy were not acquainted at this time and they were not cognizant of each other's work [8]. Some researchers still feel the importance to distinguish these techniques, and some of them use their names as synonyms for the same technique, which is called PDM today. Although the rise of the Precedence Diagramming Method (PDM) was not as straightforward as that of the previously mentioned techniques, there is no doubt that PDM has become the prevalent technique of our time due to the flexibility provided by its different precedence relations.

# 2 FOUNDATIONS AND PROBLEMS

## 2.1 PERT

The original Program Evaluation and Review Technique (PERT) [2] is an activity-on-arrow network with one start and one finish event. These two events represent the beginning and the end of a project. The logic of the project is depicted by a directed, acyclic graph in which the vertices of the graph represent the events, while the arrows represent the tasks. An event occurs when all preceding activities have been completed; after that the succeeding tasks can start.

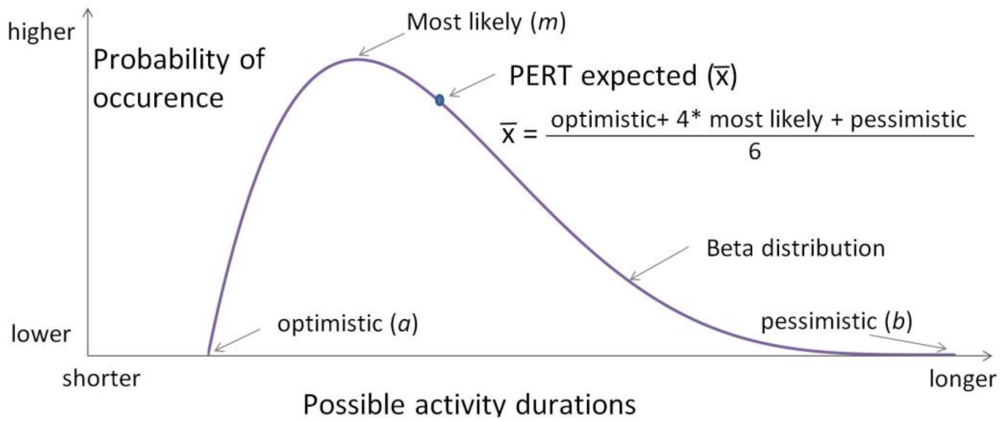



*Figure 4. Typical density function of the PERT-beta distribution*

Activity durations are defined by stochastic variables that are assumed to be independent of each other. The distribution of the activity durations follows a so-called PERT-beta distribution (Fig. 4), which can be defined by the so called three-point-estimation. The main goal of PERT analysis is to create the distribution of the project duration. According to PERT theory, the project duration has a normal distribution, with the mean being the result of a time analysis based on activity mean durations ($\bar{x}$) (see Fig. 4 for the calculation of expected values) and the variance being equal to the sum of the variences of the activities on the critical path. These calculations are based on the central limit theorem of mathematical statistics. PERT has received a great deal of criticism since its "birth". These critiques can be classified into four classes, as follows:

- Critiques of the three-point estimation (Three point estimation cannot be used to define activity distribution without ambiguity) [12-15].
- Critiques of the proposed activity distribution (Why is Beta assumed for the distribution of the activity duration, instead of other, maybe better distributions?) [16-22].
- Critiques of the optimistic result of the PERT calculation. (PERT works only if not more than one path can be critical, (see Fig. 5. Original PERT result in the same distribution for the 10 path network)) [23-29].
- Critiques about omitting activity calendars (the distribution of the project duration does not follow normal distribution even in the case of the simplest one chain network if different calendars are applied. (Fig. 6)) [30]

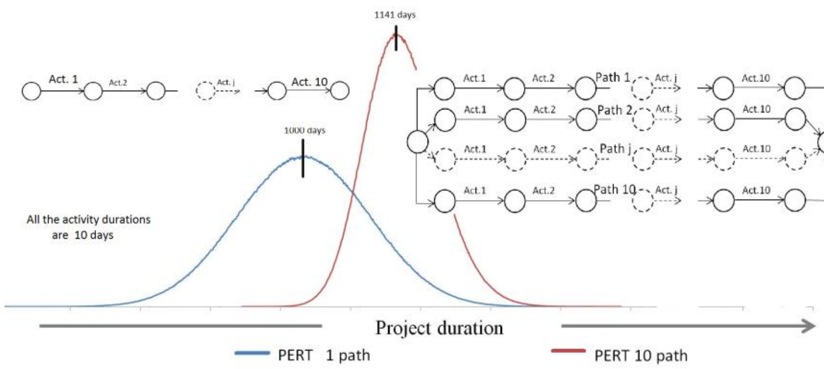



*Figure 5. Distribution of the project duration of a 1 chain and a 10 chain network*

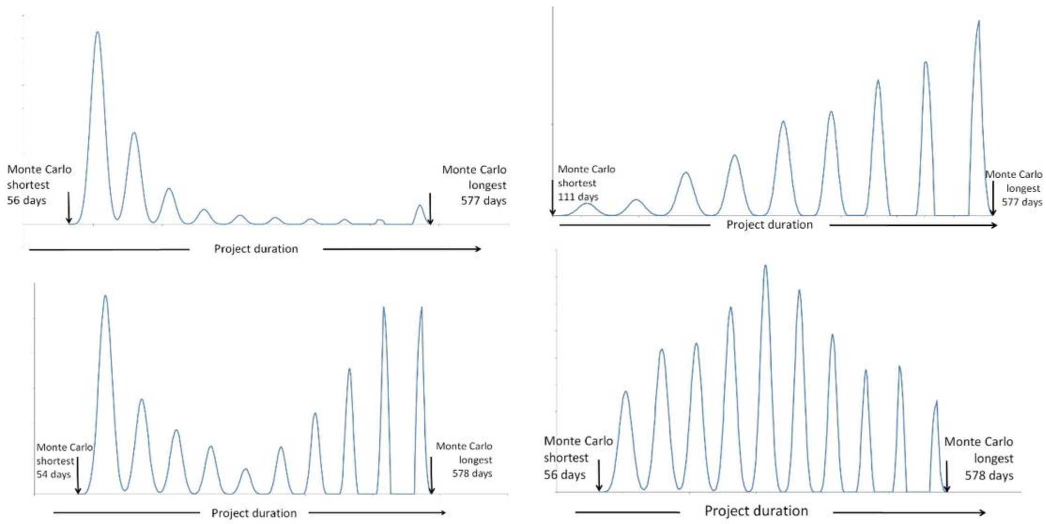



*Figure 6. The effect of the different activity calendars on the distribution of project duration based on the same one chain network [30]*

The application of a Monte Carlo simulation [31] offers a solution for all the calculation problems noted above. It can handle multiple competing paths, any kind of activity duration distributions, and calendars as well. It is fast enough to run a vast number of instances within a reasonable amount of time, and can be used on a network containing more complicated precedence relationships.

## 2.2 CPM

CPM possesses a similar topology to PERT. The basic difference is in how it handles activity durations. In the original CPM model, it is assumed on one hand that every activity has a normal duration, which is based on an execution using normal technology, normal working weeks and working days, and an average resource load. The so called normal cost is associated directly with the normal duration. On the other hand, some of activities can be accelerated by using longer shifts, faster technologies and applying more workforce and machines. The fastest activity duration is called the crash duration and the associated direct cost is called the crash cost. It was also assumed that the crash cost is greater than the normal cost, and the curve in between these costs is linear (Fig. 7).

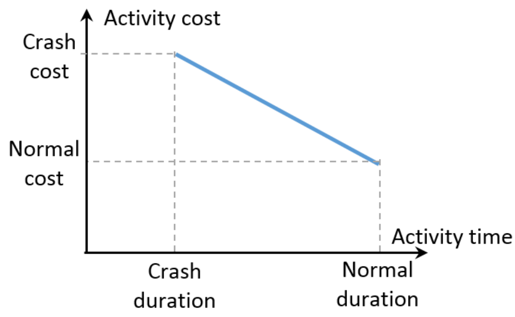



*Figure 7. Assumption of time vs cost of the original CPM model.*

It is obvious that freely changing activity durations between these boundaries results in different project durations and a different direct project cost. The goal of the original CPM model was to find the minimal project cost for all the possible project durations – that is to define the lower envelope of Fig. 8.

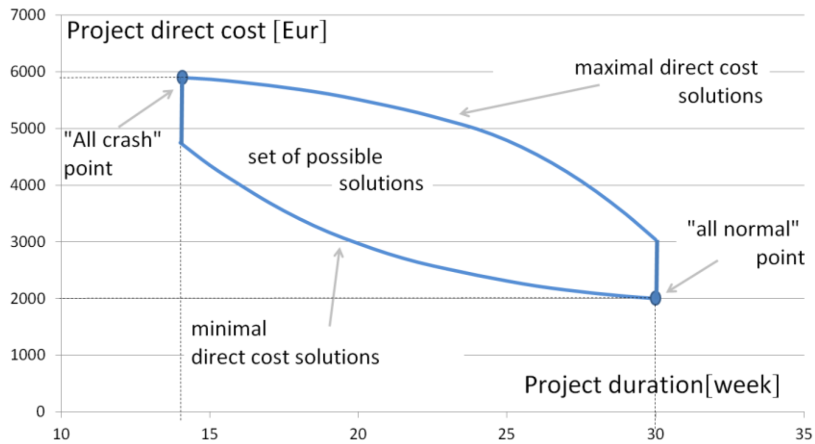



*Figure 8. The set of feasible solutions of the CPM model.* [38]

The solution that was developed by the research team in 1957 was based on linear programming, which was developed by Dantzig [32] during World War II. In the following years, mathematicians produced more and more beautiful and elegant solutions for the CPM model, based on e.g. a network flow model [33], or on the dynamic programming technique [34]. According to the author's opinion, the most elegant solution was developed by Klafszky [35]. The original algorithm assumed that the cost curve is linear between the crash and normal cost of the activities. This limitation was later relaxed in different ways by allowing discrete points or non-linear time-cost curves. [36]. Finding the maximal cost solution for the CPM problem, that is the upper envelope of the solution set of Fig. 8, is the result of Crandall and Hajdu [37, 38]. Heuristic solutions have also been developed to solve the CPM model [6] [39], and to ease the calculations in the absence of computer tools. However, these methods have no practical importance in the area of personal computers. It is interesting to note that the majority of the planners and even teachers use the term CPM simply as a synonym for time analysis on an activity-on-arrow (AOA) network, or for network techniques in general, and only a small proportion of the users know that CPM originally was a cost optimization technique.

CPM was very popular in the sixties and seventies, but its usage has rapidly decreased parallel to the increasing popularity of the PDM method. This is due to some fundamental problems with CPM and some major methodological issues. As has already been discussed earlier, AOA portrayal puts an extra effort on planners. In addition, the events-on-node structure does not give enough flexibility for modelling complicated technological and organizational logic. These problems were overcome by applying the least cost scheduling problem on PDM networks [40, 41], but the major methodological problem of precisely defining the crash durations and the associated crash cost still remains a daunting, and therefore omitted task.

## 2.3 PDM

In today's practice, the term PDM means an activity-on-node network consisting of: a) activities with given durations, assuming constant intensity and b) logical relations between activities, called precedence relations. These precedence relations prescribe the minimum necessary time between the end-points of the activities. The goals of using such constructs are to define the minimum project duration necessary to finish all the activities in the network, and to define the earliest possible start and latest possible finish dates for the activities. Some practitioners also use maximal relations in order to describe the maximum allowable times between the related activities [38]. The basics of the PDM technique have hardly changed in recent decades, despite of the criticism it has received, especially regarding its modelling capabilities. This is in fact an interesting issue as PDM is the most flexible network technique among all. During the recent decades, a great deal of research has been done to extend the modelling capabilities of the technique. Some of them – mainly results of the author - will be discussed in the following, namely a) maximal relations, b) point-to-point relations, c) continuous relations

Maximal relations were included in the original MPM, however they were not adopted into the widespread commercial software used by the majority of planning professionals. Roy's method could handle only Start-to-Start relations, but allowed the use of minimal and maximal lags. Maximal relations have to be used when not only the minimal, but also the maximal difference between the connected points of the activities has its importance. Fig. 9 explains the meaning and the importance of the maximal relations. Fig. 9a shows a part of network where activity A - "Excavation of construction hole" is followed by activity B - "Installing a supporting shore". Materials for B will be available after finishing activity C. However, C can force activity B to start long after the completion of activity A, which can cause the collapse of the sidewalls of the hole. The right logic is to insert a maximal relation from A to B that prevents A from starting/finishing too early (Fig. 9b)

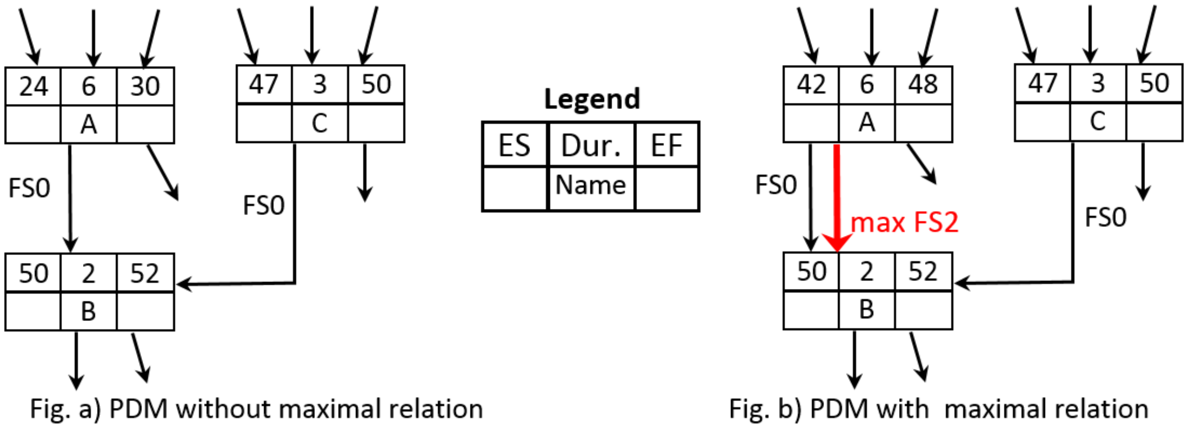



*Figure 9. Maximal relations in PDM network.*

Limitations of the PDM technique regarding the modelling of overlapping activities has been known for decades. The first step on the road to better modelling of overlapping activities was the development of point-to-point relations. Point-to-point relations can connect not only the end-points of the activities, but also any of their internal points. Connected inner points can be defined using time or work units (e.g. work days or meters). This allows overlapping to be modelled at an acceptable level, using relatively short sections connected with point-to-point relations. The development of point-to-point relations was made independently in a number of parallel studies, which gave new names to PDM such as the chronographic approach [42, 43], Bee-line Diagramming Method [44, 45], Relationship Diagramming Method [46], and Graphical Diagramming Method [47]. The common feature of all these developments is that they have made possible the establishment of logical relations between the inner points of the activities. The point-to-point denomination and the correct mathematical model comes from Hajdu [48], who also pointed to the fact that traditional precedence relations (SS, SF, FF and FS) are a specific manifestation of point-to-point relations, namely when the defined points are the end-points of the activities. Point-to-point relations can be seen in Fig. 10.

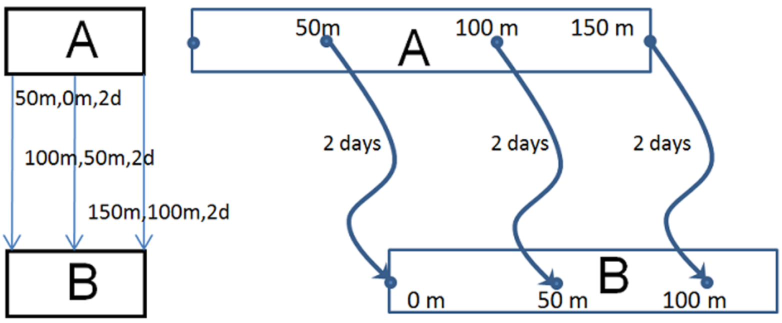
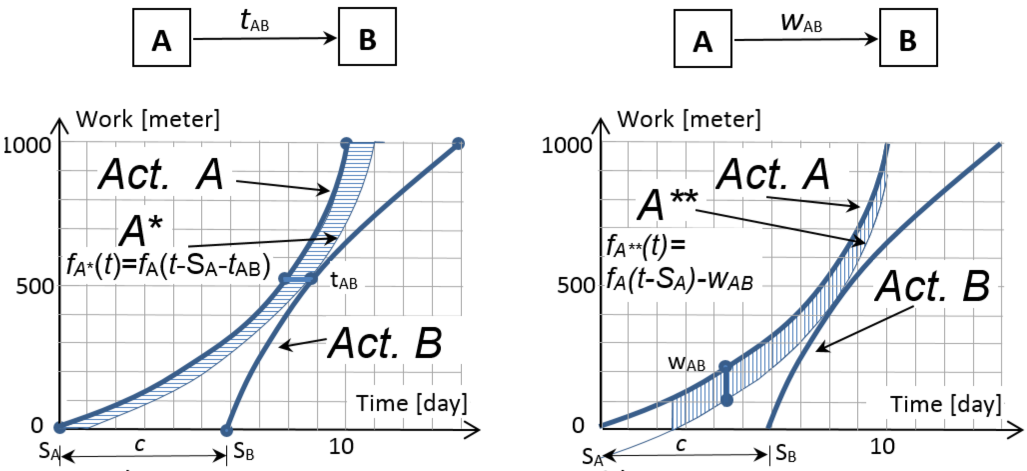



*Figure 10. Point-to-point relations for better modelling overlapping.*

Hajdu has also shown that point-to-point relations suffer from the same drawback as end-point relations, in that they control only the end-points of the fragments, and if an unacceptable situation arises within segments the model will not recognize this [49]. Consequently, point-to-point relations give theoretically correct solutions for overlapping activities only if the number of segments is infinite, and the size of the fragments approaches zero.




a) Continuous relation with time gap    b) Continuous relations with work gap

*Figure 11. Continuous relations with time and work gap.*

This revelation has led to the definition of continuous relations [50]. Continuous relations are the theoretically perfect relations for defining activity overlapping since all the points of the activities are controlled. Continuous relations can be defined by using a time and work gap as can be seen in Figure 11.

## 3 CONCLUSIONS AND FURTHER RESEARCH

The practice and the level of scheduling applications have been lagging behind scheduling theory for decades. A methodology that can ease the application of the more sophisticated developments is also missing. However, there are some creative applications that offer some of these missing features. In the near future, it could become possible for every kind of logic and all kinds of activity functions to be perfectly modelled. Once this has been done, the main problem of creating good plans will be the human factor. Projects tend to be so complex and difficult that no planners and no planning teams will be able to overview all the aspects of the projects. The author's opinion is that once the required modelling capabilities have been developed, research will next turn to developing Knowledge-Based (KB) systems that use KB techniques to support human decision-making during the course of project planning.

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