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ABSTRACT

The scheduling of projects has gained increasing attention since the introduction of PERT and CPM. Both the scheduling literature and the software scheduling packages rely on heuristic and optimal procedures to schedule projects under various assumptions. However, there is still room for improvement by incorporating specific characteristics into the scheduling procedures.

In this paper we describe the scheduling of a real-life project that aims at the construction of a tunnel at the Westerschelde in the Netherlands. In doing so, we show that so-called work continuity is the main issue during the scheduling phase. No software package, however, is able to incorporate this requirement in an exact way. We compare different possible schedules under various assumptions and prove the necessity of this new feature.

Keywords: Project Management; Work Continuity Constraints; Real-life scheduling.

1 INTRODUCTION

In this paper we focus on a huge project with a groundbreaking boring technique at the Netherlands: the westerscheldetunnel. This tunnel provides a fixed link between Zeeuwsch-Vlaanderen and Zuid-Beveland, both situated in the Netherlands (see figure 1). It is a bored tunnel with a length of 6.6 kilometres. There are two tunnel tubes and in each tube, there are two road lanes.

Insert Figure 1 About Here

In 1996, the national and the provincial government of the Netherlands assigned the construction of the tunnel by public tender to Kombinatie Middelplaat Westerschelde (KMW), a combination of six companies (Bam infrabouw, Heijmans, Voormolen bouw, Franki construct, Philipp Holzmann and Wayss & Freytag). The total project (the main tunnel, 22 kilometres service roads, several entry roads and viaducts, toll square, etc…) took 5 years to complete. The construction started at the end of 1997 and the completion date was 14 March 2003. The cost of the project was 750 million euro.

The construction of the tunnel was a technically unique project. Most tunnels in Europe are built in hard, rocky material. Never before in Western Europe has a tunnel so long or so deep been bored through relatively soft substrates such as sand and clay. The deepest point lies 60 metres below sea level. The construction logistics were extremely complex because many different actions had to take place simultaneously and so they had to be very well planned. The degree of difficulty of the work was high, especially because of depth of the tunnel and building activities. At the deepest point, the pressure was seven bar. For more general information, the reader can visit http://www.westerscheldetunnel.nl.

In the next section, we briefly describe a subpart of the project, i.e. the transverse links.

2 DESCRIPTION OF THE PROJECT

Every 250 metres the tunnel tubes are connected by transverse links (sometimes referred to as cross passages), as displayed in figure 2. Under normal circumstances, the doors to the transverse links are locked. In case of an emergency, they are unlocked automatically and one can walk to the other tunnel tube. Consequently, the emergency services can use this road to reach the site in case of an accident.

Insert Figure 2 About Here

The transverse links account for ten percent of the construction budget. Construction is done by means of a freezing technique (figure 3). This guarantees watertight transverse links and does not harm the environment. The Westerschelde Tunnel is the first time for the freezing technique to be used on such a large scale.

Insert Figure 3 About Here

First, 26 pipes fitted with drill heads are bored from the eastern tube to the western tube (activity 1 of figure 5) and a refrigeration unit is built in the eastern tube (activity 2). After that, a brine solution that has been cooled to -35°C by the refrigeration unit (figure 4) is pumped into 22 of these steel pipes (activity 3 or 4, dependent on whether it is sand or clay that has to be frozen). Two of the pipes are used to monitor the progress of the freezing activity and one pipe is for drainage. When the ice around the future transverse link is sufficiently thick, the installation of the link can begin.

Insert Figure 4 About Here

In the western tube, the future entrance to the link is opened and the frozen ground is excavated step by step with a cutting machine (activity 5). To prevent the ice capsule from deforming under the great pressure, a layer of gunited concrete is immediately sprayed under high pressure against the exposed ground. In this way, metre by metre, a concrete outer wall is created. Subsequently watertight foil, which prevents the mixing of thawing water and concrete, is applied (activity 6). After that, shuttering is laid for the spraying of concrete for the inner casing that will form the floor (activity 7) and also the wall and the roof (activity 8) of the transverse link. Then the shuttering is removed (activity 9) but the surrounding ground is still being frozen to discharge the concrete (activity 10). Only when this concrete has hardened sufficiently the freezing process can be discontinued. Finally, the refrigeration unit can be drawn off (activity 11). The links are completed at a later stage.

In figure 5, we display the unit activity-on-the-node network of the subproject ‘build transverse links’ with 11 activities. Although this unit network is a simplified and adapted version of the real network, it is useful to illustrate our overall results. All technological precedence relations are of the finish-start type with a time-lag of zero (FS = 0), except where indicated.

Insert Figure 5 About Here

Activities denoted by the black bars are so-called hammock activities. These activities have a variable duration which is equal to the time-span between the start and end of this hammock activity. Hammock 1 denotes the total subproject (transverse links) per unit and has a duration which equals the total makespan of the subproject. Hammock 2 refers to the time span that the freezing machine is necessary during the execution of the subproject. Figure 5 reveals that this freezing machine is needed between the start of activity 2 and the finishing of activity 10. The freezing activities are split into two subactivities: hammock 3 refers to all freezing activities on the gunited concrete, while hammock 4 refers to freezing activities during the construction of concrete.

Although the freezing machine is an important resource that is necessary during the construction of a transverse link at each unit, the crews that pass along the units are also considered as an important resource type. In the network, we incorporate 5 different crews (referred to, for the sake of simplicity, as crew 1, crew 2, crew 3, crew 4 and crew 5), i.e. activity 1 needs crew 1, activity 2 needs crew 2, activity 5 needs crew 3, activity 7 needs crew 4 and activity 8 needs crew 5. The crews mainly consist of ordinary employees and specialists.

The network displayed in figure 5 is a unit network, which means that this is a graphical representation of the subproject for only one unit. As mentioned before, a transverse link has to be built every 250 metres, resulting in 26 cross passages in the tunnel. The unit network will, therefore, be repeated for 26 times, as will be explained in the next section. Each unit makes use of the freezing machine while the different crews pass along the units.

3 ANALYSIS OF THE PROJECT

3.1 Features of the project – work continuity constraints

The construction project under study involves the scheduling of project activities subject to resource constraints. The main resources are the crews performing the work along the units and a large freezing machine needed during the construction process. Similar construction scheduling problems have been discussed extensively in literature and focus on two main characteristics:

(i) *Construction projects are often characterized by repeating activities that have to be performed from unit to unit, and*

(ii) *It may be necessary to incorporate the learning effects into activity time estimates in order to improve the accuracy of schedules*

Characteristic *(i)* has been described in literature for the scheduling of highway projects, pipeline constructions and high-rise buildings in which the crews perform the work in a sequence and move from one unit of the project to the next. The repetitive processes of these construction projects can be classified according to the direction of successive work along the units. In *horizontal repetitive projects* the different processes are performed horizontally, as seen in pipeline construction or paving works. These construction projects are often referred to as *continuous* repetitive projects or *linear* projects due to the linear nature of the geometrical layout and work accomplishment. When progress is performed vertically, we refer to *vertical repetitive projects*, among which high-rise building construction is the classical example. Rather than a number of activities following each other linearly, these construction projects involve the repetition of a unit network throughout the project in discrete steps. It is therefore often referred to as *discrete* repetitive projects. Kang et al. (2001) argue that construction projects can consist of both horizontal and vertical repetitive processes among several multi-storey structures and refer to this type as *multiple repetitive projects*.

Characteristic *(ii)* allows the incorporation of crew productivity, differences in amounts of work between units or learning effects of crews and has been investigated by Amor (2002), Amor and Teplitz (1993, 1998), Badiru (1995), Shtub (1991) and Shtub et al (1996). El-Rayes and Moselhi (1998) distinguish between typical and atypical repetitive activities. *Typical repetitive activities* are characterized by identical durations over all units, while *atypical repetitive activities* assume variation of duration from one unit to another and consequently, allow the incorporation of learning effects. This variation can be attributed to variations in the quantities of work encountered or crew productivity attained in performing the work of these units (Moselhi and El-Rayes (1993)).

The project under study fits very well into this framework. Firstly, learning effects are a matter of degree since the project involves the repetition of 26 units. Note that learning effects can be considered as positive (experience of crews or reduction of errors), as well as negative (increasing complexity). Secondly, it is crucial in scheduling these project types to ensure the uninterrupted usage of resources of similar activities between different units, as to enable timely movement of resources (crews) from one unit to the other, avoiding idle time. This feature is known as *work continuity constraints*.

In the next section, we show the schedule of the project without taking the necessity of work continuity into account. In section 3.3 we introduce the work continuity constraints and compare it with the original schedule. In section 3.4 we present different scenarios and discuss the financial implications.

3.2 Earliest start schedule

In this section we schedule the project with classical software packages using the well-known CPM technique. In doing so, we construct a Gantt chart in which all activities are performed as soon as possible (i.e. an earliest start schedule (ESS)). We use the activity time estimates as shown in figure 6. For the sake of clarity, we restrict our analysis to units 4 to 26 since the networks of units 1-3 have a different morphological structure than the one depicted in figure 5. This does, however, not harm our overall results.

Insert Figure 6 About Here

Clearly, the ESS does not take the work continuity constraints into account and consequently, does not assure the minimization of idle time of resources. Although work continuity constraints are often linked with crew idle time, we use, in the sequel of this paper, the more general term *resource idle time*, since the minimization of idle time of resources may not be restricted to crews only. As an example, De Boer (1998) introduced spatial resources as a resource type that is not required by a single activity but rather by a group of activities. Examples are dry docks in a ship yard, shop floor space or pallets. Since the spatial resource unit is occupied from the first moment an activity from the group starts until the last activity of the group finishes, work continuity constraints can be of crucial importance. Gong (1997) has introduced the concept *time dependent cost (TDC)* as a part of the project costs that changes with the variation of activity times. The TDC of a cost times is then the product of unit time cost and service time. Goto et al. (2000) elaborate on that concepts and argue that the service time of a *time dependent cost resource* is the time duration starting form the first use and ending at the last. They refer to the use of a tower crane in the construction industry and argue that the reduction of waiting times of TDC resources naturally reduces the time dependent cost. These research papers motivated us to use the general term ‘resource idle time’ rather than the more specific ‘crew idle time’.

In figure 7 we display the Gantt chart (units 4 and 5) obtained by the ESS schedule, assuming that the project starts at the beginning of January, 2003. This schedule clearly results in a lot of resource idle time, both for the freezing machine (within each unit) and for the crews (along the units). The idle time of crews, on the one hand, results from time-lags between the finishing of work at one unit and the start at the next unit. The idle time of the freezer, on the other hand, appears within units, due to the earliest starting time of all activities. As an example, the idle time between units 4 and 5 of crew 2 and the idle time of the freezer at unit 5 has been indicated at figure 7. The total crew idle time in the ESS schedule amount to 165 days while the freezing machines are idle for 343 days in total. The total scheduled project duration of the transverse link subproject equals 380 days (for the sake of simplicity, we ignored weekends and holidays). Note that we assume that we have access to an unlimited number of freezing machines, such that parts of the projects at different units can be performed in parallel. If this is not the case, the total idle time of the freezing machines will change dramatically. This is the subject of 3.4, in which we analyze different scenarios.

Insert Figure 7 About Here

In the next section, we schedule the project by minimizing the resource idle time.

3.3 Minimizing resource idle time

As stated earlier, we assume that a project is represented by an activity-on-the-node (AoN) network (see figure 5) where the set of nodes, N, represents activities and the set of arcs, A, represents the precedence constraints. Since progress is performed in discrete steps (as in vertical repetitive projects), we assume that this network is repeated in K units (K = 26).

The duration of each activity i at unit k is denoted by d_{ik} ($1 \leq i \leq n$ and $1 \leq k \leq K$ with $n = |N|$). In a similar way, we denote the starting time of activity i at unit k by s_{ik}. Consequently, we extend the original unit network of figure 5 to a large network consisting of n repeating activities between K units. This network is extended with a dummy start activity 0 at the first unit and a dummy end node $n + 1$ at the last unit, denoting the start and finish of the project.

The project scheduling problem with work continuity constraints can be formulated as follows:

$$\text{Minimize} \sum_{i \in N'} (s_{iK} - s_{i1}) \qquad [1]$$

Subject to

$$s_{ik} + l_{ijkk} \leq s_{jk} \qquad k = 1, \ldots, K \text{ and } \forall (i, j) \in A \qquad [2]$$

$$s_{ik} + l_{iik,k+1} \leq s_{i,k+1} \qquad i = 1, \ldots, n \text{ and } k = 1, \ldots, K-1 \qquad [3]$$

$$s_{01} = 0 \qquad [4]$$

$$s_{n+1,K} \leq \delta_{n+1} \qquad [5]$$

$$s_{ik} \in \text{int}^{+} \qquad i = 1, \ldots, n \text{ and } k = 1, \ldots, K \qquad [6]$$

where l_{ijkl} denotes the time-lag between activity i on unit level k and activity j on unit level l. These time-lags denoting the different types of generalized precedence relations can be represented in a standardized form by reducing them to minimal start-start precedence relations as shown by the transformation rules of Bartusch et al. (1988). As an example, l_{ijkk} has to be replaced by d_{ik} in Eqs. [2] to model the simple CPM case where only minimal precedence relations with zero time-lags are involved.

The objective in Eq. 1 denotes the work continuity constraints and minimizes the resource idle time between similar activities at different units. The set N' is used to denote the set of activities that make use of the resource type that is subject to resource idle time minimization (i.e. freezing machines or crews in this case). We note that the word 'constraint' is somewhat confusing since the work continuity of the schedule is guaranteed in the objective function of the model. Since the resource idle time is measured for resources that shift between units, it is sufficient to minimize the timespan of activities between the first and last unit. Indeed, these resource are needed at the start of the activity at the first unit and will only be released at the completion of this activity at the last unit K. Consequently, the starting times of all intermediate activities have no influence on the idle time of this resource and are therefore not included in the objective function. The constraint set given in Eq. 2 maintains the (generalized) precedence relations among the activities of the project network at each unit. The constraint set in Eq. 3 maintains the (generalized) precedence relations among similar activities between consecutive units. Eq. 4 forces the dummy start activity 0 to start at time zero and Eq. 5 forces the dummy end activity n + 1 (and consequently the project) to end on or before a negotiated deadline δ_{n+1}. Eq. 6 ensures that the activity starting times assume nonnegative integer values.

This scheduling problem can be efficiently solved by an adapted version of the procedure by Vanhoucke et al. (2001). In doing so, it takes the minimization of resource idle time into account and new results compared to the traditional CPM schedules will be obtained. More precisely, total idle time can be reduced from 165 days to 107 days for crews and from 343 days to 5 days for the freezing machine. The total project duration still remains 380 days.

The new schedule has positive implications on the outline of costs of the project. The costs of the crew are generally as follows: An ordinary employee has a cost of – on the average - € 40/manhour while a specialist has a cost of – on the average - € 60/manhour. Consequently, the average cost of one man-hour amounts to € 50. Each crew consists of 3 people that work for 8 hours/day, resulting in a total cost of 50 * 3 * 8 = € 1,200 per day. The freezing machine has a cost of € 3,000/day and is needed at each unit from the start of activity 2 until the completion of activity 10.

Taking these cost figures into account, we derive the following outline of costs for the earliest start schedule of section 3.2. The crew idle time takes 165 days, resulting in 165 * € 1,200 = € 198,000 while the idle time of all the freezing machines results in a cost of 343 days * € 3,000 = € 1,029,000. The new schedule minimizes the resource idle time and results in the following outline of costs. The crew idle time cost amounts to 107 days * € 1,200 = € 128,400 and the idle time off all the freezing machines has a cost of 5 days * € 3,000 = € 15,000. The difference in idle time cost between the two schedules amounts to € 1,083,600.

3.4 Different scenarios

In the previous section, we assumed that we have access to an unlimited amount of freezing machines. In doing so, a lot of the activities of different units can be performed in parallel. Due to the expensive nature of these machines, it is almost impossible to rely on a large amount of freezing machines. In table 1 we display the results for a limited amount of freezing machines. Since a decrease in the number of freezing machines prevents the parallel execution of consecutive units, the total project duration will automatically increase (similar to resolving resource conflicts in a resource-constrained project scheduling problem). In the table, we refer to ‘deadline’ as the total project duration, ‘CIT’ as the crew idle time and ‘FIT’ as the freezing machine idle time. The column ‘Min-CPM’ has been created to display the results of the schedules with the classical CPM tools, while the column ‘Min-WC’ display the results with the approach described in this paper. This table reveals, on the one hand, that more freezing machines result in slightly more idle time of this resource but a shorted project deadline. Indeed, the freezing machine is used within each unit, and consequently, the more freezing machines we have, the more the units can be performed in parallel. Moreover, the larger the total project duration, the more degrees of freedom to schedule all the activities and the lower the idle time of the freezing machine. The idle time of crews, on the other hand, reveals an opposite behaviour: the larger the increase in the project deadline, the larger the idle time of crews. This is mainly because of the limited amount of resources (the freezing machine in this case). Indeed, due to a limited amount of freezing machines, work at one unit can only start after the finishing of the previous unit. In doing so, the crews are idle for quite some time since the freezing machine is then the bottleneck resource that determines the progress of the project.

Insert Table 1 About Here

In section 3.3, we have outlined the cost difference between the two schedules, assuming an unlimited amount of freezing machines. This corresponds to the row with 12 or 13 freezing machines of table 1. A similar analysis can be done for all other rows of this table, revealing the advantages of incorporating resource idle time minimization.

4 CONCLUSIONS

In this paper, we relied on real-life data of a construction project of a tunnel in the Netherlands. In analysing the data, we detected some shortcomings in the classical software packages. While the vast amount of software packages focus of resource levelling and time minimization, they do not take the work continuity constraints into account. In this paper, we have shown that the incorporation of work continuity constraints takes the minimization of resource idle time into account.

The incorporation of work continuity constraints in the schedule has revealed two important insights. Firstly, the minimization of resource idle time results in a dramatic decrease of the cost of the resource use. Indeed, resource idle time results from the fact that one has to pay for this resource while it is not really necessary. In this paper, we have referred to crews that have to wait to pass along units and a freezing machine that might be in operation while no real work is done during that time. Secondly, the minimization of resource idle time involves a trade-off between cost of idle time and project deadline increase. Indeed, the larger the project deadline, the more degrees of freedom in scheduling the activities and, consequently, the lower the resource idle time. We revealed an opposite effect for the crew idle time, but this was mainly due to a limited amount of the bottleneck resource (i.e. the freezing machine) that prevented progress of the project.

The problem under study is of crucial importance in projects which are characterised by repeating activities that have to be performed from unit to unit, such as highway projects, pipeline constructions and high-rise buildings. Resources that move along the units can be the subject of idle time between these units. Work continuity constraints can also be of importance for the minimization of within-unit idle time, as is the case for the freezing machine. Consequently, the problem under study can also be crucial in projects without repeating activities but with important, capital-intensive resources such as machines, specialized consultants, etc…

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FIGURE 1

Geographical situation of The Westerschelde Tunnel (Source: KMW)

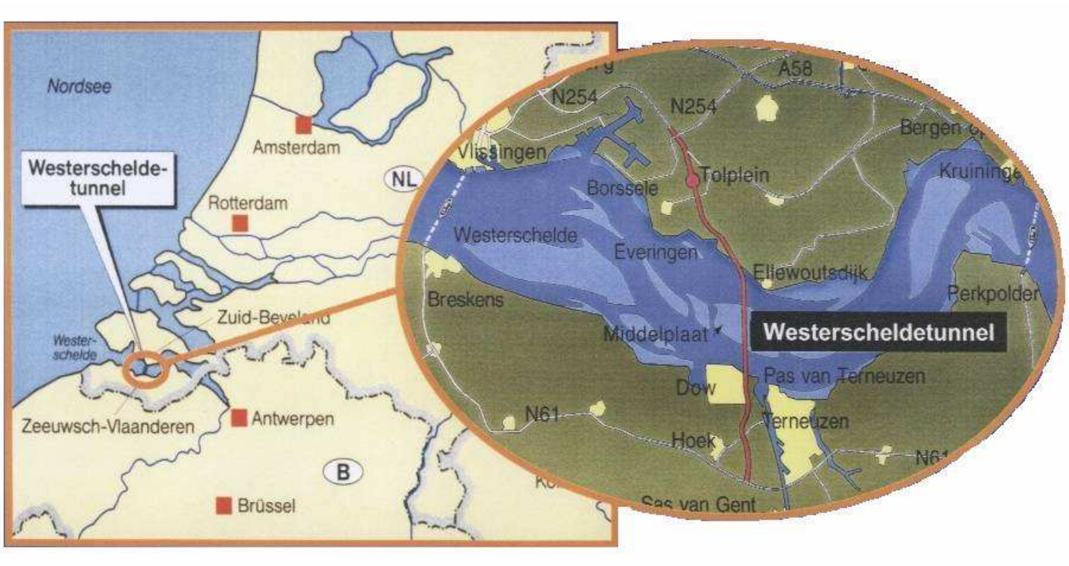

FIGURE 2

Drawing of a transverse link (Source: KMW)

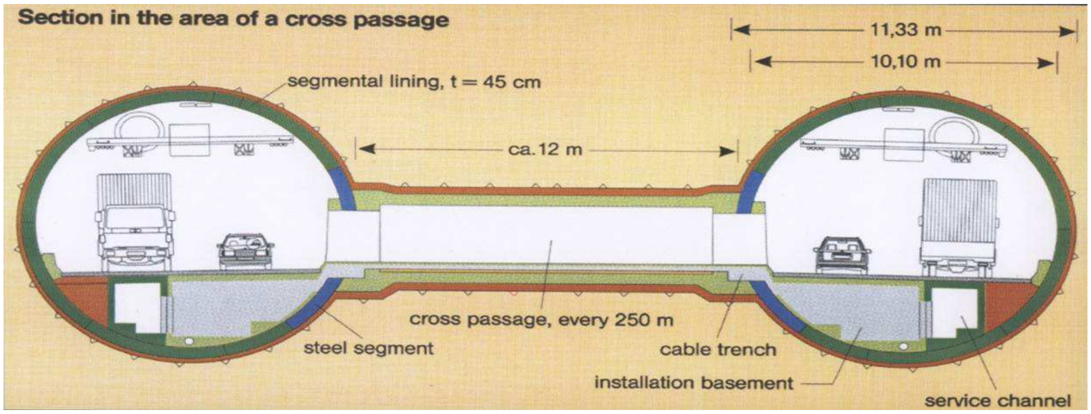

FIGURE 3

Freezing technique (Source: KMW)

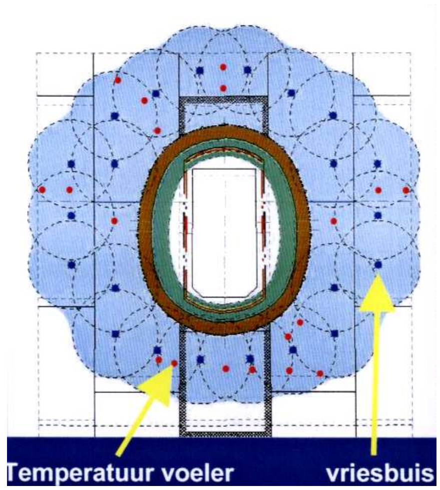

FIGURE 4

Refrigeration unit (Source: KMW)

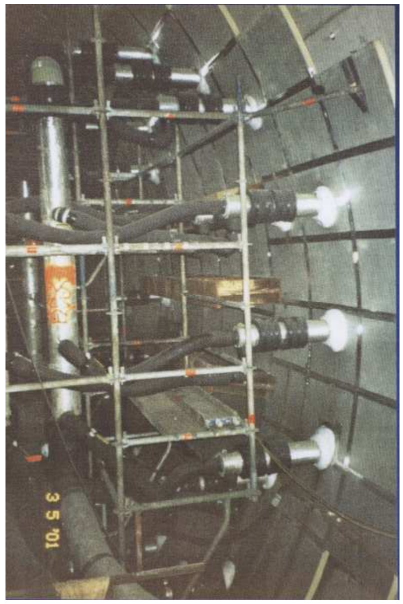

FIGURE 5

The unit project network of the subproject "build transverse links"

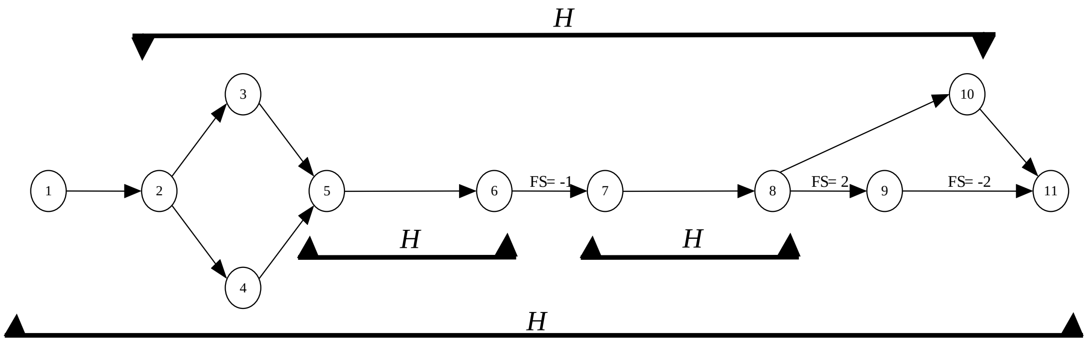

FIGURE 6

The activity time estimates of the project under study

activity \ Unit	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1	17	11	14	7	9	9	11	9	9	12	14	11	12	12	13	10	7	7	9	8	9	9	12
2	9	12	10	4	9	8	4	5	4	6	4	7	5	5	5	5	4	5	4	5	5	4	4
3	0	0	0	39	38	38	42	47	50	47	47	40	42	40	0	57	0	0	0	0	0	0	0
4	51	33	41	0	0	0	0	0	0	0	0	0	0	0	39	0	48	44	38	45	53	31	42
5	25	1	10	7	15	9	10	12	6	9	8	10	9	7	10	8	19	12	17	12	8	10	12
6	8	12	8	10	11	8	9	10	8	9	10	11	9	9	4	9	9	9	4	8	10	6	9
7	1	1	3	3	3	3	4	7	5	4	5	5	5	3	4	4	2	3	4	6	5	3	4
8	9	8	4	10	6	5	4	7	5	10	6	10	7	5	3	6	4	5	4	4	7	9	4
9	2	2	2	5	2	4	2	2	2	2	2	2	2	3	2	3	2	2	2	2	2	2	2
10	12	8	5	9	10	5	11	10	23	19	10	11	10	4	11	8	9	11	10	5	10	4	7
11	2	7	1	3	2	4	5	4	3	3	4	5	3	4	4	5	2	4	4	5	3	4	4

FIGURE 7

Gantt chart obtained by the ESS of the project

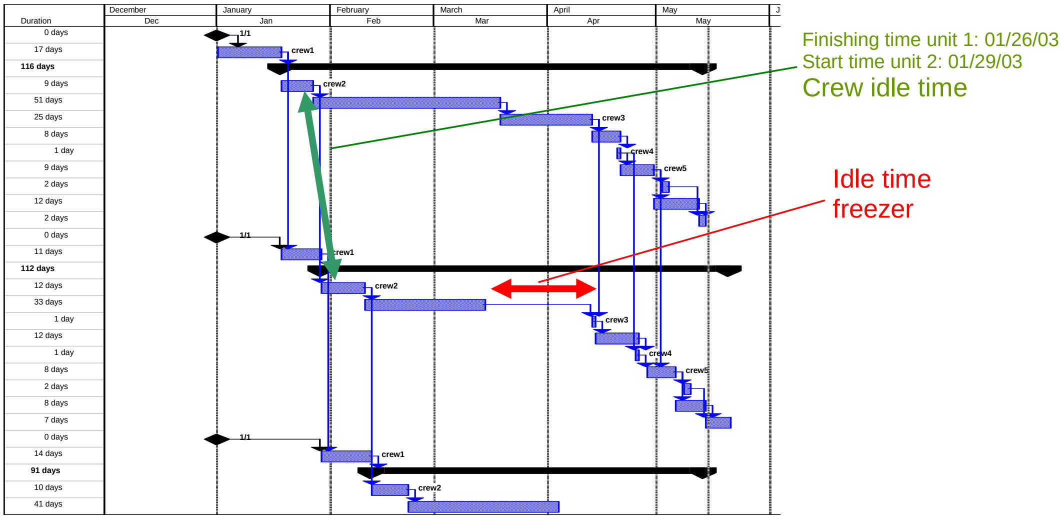

TABLE 1

Idle time calculations under different scenarios

		Min-CPM		Min-WC	
Freezers	Deadline	CIT	FIT	CIT	FIT
1	2101	3641	0	3641	0
2	1124	1687	39	1687	0
3	788	1015	82	1015	0
4	629	696	161	696	1
5	527	493	161	493	0
6	462	363	180	363	2
7	436	310	353	310	1
8	405	204	342	204	1
9	380	167	305	162	1
10	380	165	347	129	3
11	380	165	343	117	5
12	380	165	343	107	5
13	380	165	343	107	5