Engineer-to-order Project Schedule Planning through a probabilistic simplified approach: a case study

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ABSTRACT

Schedule management is a particularly important activity for companies that manage their business with an engineer-to-order approach. In many cases, especially in smaller enterprises, projects duration, estimated applying deterministic approaches or even referring to own experiences, are significantly inaccurate or overestimated. For these reasons, in this paper which is the extended version of a previous work presented at the Summer School "F. Turco", authors propose an application of a probabilistic simplified approach on a case study comparing the results to those deriving from deterministic approaches and actual durations. Methodologies have been applied according to the sequence defined by the Project Management Institute. To estimate activities durations both physical and statistical models have been used, instead of the entire project duration has been calculated through a critical path method. Results comparison shows that adopting a statistical approach leads to tolerable complications but allows to get more accurate estimations. Moreover, the possibility to consider the most probable, optimistic and pessimistic duration allows the enterprise to take into account potential risks that could delay project conclusion. This application is focused on a particular case study nevertheless conclusion could be common to many other organizations.

Keywords: Project scheduling; Engineer-to-order; Probabilistic method.

1 INTRODUCTION

Competitiveness is the enterprise's capability to provide better quality services and products compared with domestic and foreign competitors (Yanrong, Yu and Kang, 2011). The basis of competitiveness is creating value based on sustainable growing (Fleaca, Fleaca and Maiduc, 2017). Enterprises adopting engineer-to-order (ETO) approach are obliged to face the dynamics of business increasing their competitiveness focusing their efforts on research and development (Mikkola, 2001). In general, ETO manufacturing leads to a project-oriented approach applied to develop specific solutions following customer requirements (Kozjek *et al.*, 2018). Furthermore, applying ETO approach, production does not start before customer order confirmation (Vaagen, Kaut and Wallace, 2017). ETO enterprises can surely use concepts of project management to better perform and increase their competitiveness (Boznak, 1993).

A project is conventionally defined as a temporary endeavor to achieve the desired purpose (Hall, 2012). Obviously, a project has some constraints represented by the “iron triangle” (De Wit, 1988) which makes the project management particularly difficult from both theoretical and practical perspectives. Despite the availability of theoretical methods, it is quite difficult to respect all three constraints (Collier *et al.*, 2018). Failure risks depend on difficulties, human skills and other uncertainties especially for new projects (Mummolo, 1997). In this context, it is not easy to establish resources and activities durations to respect constraints at best when the final product is innovative or never done before.

In a competitive market, delays in project completion can discredit reached results. For this reason, project development requires time calculation paying attention to sources and errors (Litvinov and Moskaliuk, 2018).

Today’s technical and technological competition encourages management to adopt methods and software to forecast as well as possible project duration and to maintain all the activities under control avoiding possible delays.

Project Scheduling Management (SM) (also known as Time Management) is the PM branch whose objective is the optimization of project activities respecting time opportunities and constraints. According to Westland (2007), SM is the process of recording and controlling time spent on a project. SM is composed of several methodologies and techniques designed to fix and respect a deadline. It includes a wide range of operations as well as: planning, resources allocation, goal definition, time analysis, activities monitoring, organization, scheduling, and priorities definition.

In many cases, limited knowledge about processes, possible risks, and the fear of possible underestimation lead to imprecise too long estimates (Pospieszny, Czarnacka-Chrobot, and Kobylinski, 2018). In such a scenario, the role of the project manager is to comprehend the situation in terms of risks and uncertainties, and then estimate a duration distribution (Hershauer and Nabielsky, 1972). He has to consider all the variables influencing all the activities and decide which of them are important for improving enterprise competitiveness (Aliverdi, Moslemi Naeni and Salehipour, 2013; Uzzafer, 2013). Nevertheless, the continuous innovation of processes and the availability of increasingly large amounts of data are fundamental aspects that will allow, in the near future, to abandon the traditional techniques and approach the use of machine learning methods.

For ETO enterprises, especially the smaller ones, the transition from a traditional approach to more evolved methods may not be easy because of some problems. The repetitiveness of activity sequence (typical of ETO projects) encourages project managers to adopt deterministic approaches, the uniqueness of every single project does not make available significant data, and available methods are often too complex to be applicated. To overcome these problems, in many cases physical models are adopted to estimate time durations.

This paper is an extended version of work published in Baffo et. al., (2018). The authors illustrate, through the application on a case study represented by an ETO enterprise, how a simplified probabilistic approach can provide good estimate reliability by applying a not very complex method with a restrained quantity of data necessary for its implementation.

The remainder of this paper is divided into five sections. The first section provides a short review of the relevant literature about the applications of SM. The methodology used to estimate activities and project durations is detailed described in the second section. In the third section, the description of the case study and the results of the methodology application are reported. Before the conclusion, the main results are discussed in the fourth section and finally, in the last section, general conclusions concerning this research are noted.

2 LITERATURE REVIEW

Many organizations have developed methods and standard to manage projects and all their aspects such as Project Management Institute (PMI), Office of Government Commerce called PRojects IN Controlled Environments 2 (PRINCE 2), International Project Management Association (IPMA) (Kostalova, J., Tetrevova, L., & Svedik, J., 2015). The methods of PM have been collected and defined by PMI in PMBOK (Project Management Institute, 2017). PM processes and tools have been organized in 10 knowledge areas that are:

- Project Integration Management.
- Project Scope Management.
- Project Schedule Management.
- Project Cost Management.
- Project Quality Management.
- Project Resource Management.
- Project Communications Management.
- Project Risk Management.
- Project Procure Management.
- Project Stakeholder Management

Project Schedule Management collects all the processes necessary to ensure that the project takes place and is completed according to the required timing. The traditional PM identifies two approaches to plan project duration, the deterministic approach and the probabilistic one (Józefowska, Mika and Waligóra, 2011). The deterministic approach provides a single value estimation of the project duration instead probabilistic approach yields distributions of possible durations. A typical example for the first category is represented by the Critical Path Method, the second category could be represented by the Program Evaluation and Review Technique and Monte Carlo method.

Critical Path Method (CPM) is one of the most popular methods to provide the minimal duration of a project (Ravi Shankar and Sireesha, 2009). CPM was presented in Kelley Jr and Walker (1959) and during the years many examples of application are reported in the scientific literature. This method (with the necessary changes) has been implemented in a wide range of engineering and management applications.

In Zareei (2018) CPM has been applied to organize and manage a large-scale biogas plant construction project involving many activities and many dependencies. Yang and Kao (2012) and Hegazy (2001) applied CPM to manage possible delays of general construction projects. Castro-Lacouture et al. (2009) evaluated the performance of mathematical models for determining project duration using CPM and other methods.

CPM has been demonstrated very suitable in the manufacturing industry with sets of activities, linked to each other, for which duration estimation was based on deterministic estimates made using analogies, physical and parametric models. Gupta (1991) has proposed a modification of CPM developing a methodology applicable to continuous production systems throughout the projects. Li, Zhang and Miao (2007) and Karaca and Onargan (2007) have applied CPM in general manufacturing and for special use of marble.

During the time, CPM has been applied to many other aspects of projects. Hoffman (1993) has been applied to coordinate clinical care. In Wickwire and Smith (1974) CPM has been used to manage contract claims, also has been modified and applied to regulate special systems.

Program Evaluation and Review Technique (PERT) has been used in many projects having probabilistic knowledge of activity durations (Soroush, 1993). PERT is suitable when activities duration is considered highly uncertain (Wauters and Vanhoucke, 2016). Thus, PERT does not compute duration with a probability of completion of 50% but allows to have a probability distribution (Adlakha and Kulkarni, 1989).

In scientific literature, many examples of PERT applications can be found. In some cases, PERT has been applied in the industrial area as in Kwak and Jones (1978) and Pontrandolfo (2000). In many other works, some modifications to the original method have been developed. In **Table 1** some applications of PERT and modified methods are collected.

Table 1 – PERT application in scientific literature

Reference	**Objective**
(Lootsma, 1989)	Considering that duration is estimated mainly based on the expert evaluation, authors compare traditional PERT with a modified PERT. In the modified method, duration estimations are due to fuzzy logic applications.
(Magott, 1993)	Comparing PERT applied with traditional beta distribution and the same model applied with an exponential distribution.
(Soroush, 1993)	The work introduces a modification in the traditional PERT method. Cost function has been added to each activity to consider the presence of risk. To evaluate the "optimal" or critical path, the project manager can select a path considering the probability of completion time and the correlated risks.
(Mummolo, 1997)	Modification of PERT adding uncertainty and criticality measures based on analysis of possible completion sequences of activities.
(Cottrell and Eview, 1999)	A simplified version of PERT is developed and tested. Required estimates are reduced from three to two (most probable and pessimistic), in this way it is possible to simplify the resolution.
(Pontrandolfo, 2000)	The paper proposes 2 different modifications of PERT that are applied on two case studies and results compared to traditional PERT application.
(Eddine, Benhocine, and Belouadah, 2011)	The authors propose a method to build a different network able to find a "minimal PERT" that minimizes the number of dummy activities through a series of rules to be followed in order of proposition.
(Herrerìas-Velasco *et al.*, 2011)	PERT method has been modified intervening on beta distribution. Three parameters have been added to modify the distribution and characterize results
(Aziz, 2013)	The authors focus on the calculation of the expected completion probability of repetitive construction projects through a modified PERT method.

(Hajdu, 2013)	Four categories of criticalities have been presented and discussed. Excessive simplifications lead to distorted results that many kinds of research have tried to limit.
(Acebes *et al.*, 2014)	A comparison between Earned Value method and PERT has been done. It includes also an analysis of EV developed method considering different behavior, changing data distribution from beta to exponential to normal.
(Barbara *et al.*, 2015)	The authors propose a modification of PERT capable to treat different risk categories. Project uncertainty is modeled mixing beta distribution (typical of PERT) with many different distributions representing various project risks.
(Doubravský and Doskočil, 2015)	PERT is compared with the Monte Carlo method.
(Mazlum *et al*., 2015)	In this work, PERT and CPM are used to improve the plan of an online internet branch.
(Hajdu and Bokor, 2016)	The work compares various probability distributions with the aim of evaluating the differences and assessing the impact of the accuracy of the evaluations of the individual activities. The results show that data accuracy is more important than a probability distribution
(Mishakova *et al.*, 2016)	PERT has been applied together with Earned Value to monitor the project.
(Karabulut, 2017)	PERT and Monte Carlo simulation is applied on a project leading to different results.
(Litvinov and Moskaliuk, 2018)	PERT has been compared with a method based on Rayleigh distribution. Results are used to evaluate artificial intelligence functionality.
(Sari, *et al.*, 2018)	PERT has been applied to underline bottleneck and to reduce the setup time of machines.
(Bordley, Keisler and Logan, 2019)	The authors have analyzed the possibility to use PERT in absence of uncertain deadlines.

In many cases, PERT provides not optimal results. PERT has been criticized mainly because of its tendency to underestimate project duration (Mummolo, 1997). Some improvements have been obtained adding Monte Carlo simulation or other new estimators more statistically efficient. Also, some modifications to data distribution have been tested to improve the method's accuracy (Herrerìas-Velasco, Herrerìas-Pleguezuelo and Van Dorp, 2011). Lastly, PERT has been criticized for the appropriateness of three-point estimation (Hajdu, 2013).

The difficulties in applicating and managing different SM techniques on ETO manufacturing motivated authors to propose an application of a simplified probabilistic approach. Considering that a deterministic approach, like CPM, could lead to wrong or incomplete results, the authors show that a probabilistic approach, with proper simplification, can be suitable to provide very good solutions to scheduling problems of ETO projects. For these reasons, the authors propose an application of both deterministic and simplified probabilistic approaches on a case study in order to compare the capability to estimate project duration. Both physical and statistical models, depending on data availability, have been used to estimate activities durations and reached results have been compared to state the suitability of applied methodologies. The following section describes the methodology used to apply the two different approaches and then explain the results comparing estimated durations with actual ones.

3 METHODOLOGY

In scientific literature, many approaches are available for the estimation of the project duration. In this work, authors want to refer to the schedule management processes defined by the Project Management Institute (PMI) in PMBOK (Project Management Institute, 2017). The SM methodology is developed in six main steps:

1) Plan Schedule Management: policies, procedures and documentation establishing for planning, developing, executing and controlling the project. This activity is performed once or at predefined points.

2) Define Activities: the production work packages must be breakdown into the different manufacturing activities needed to realize the product.

3) Sequence Activities: the relationships among the activities must be identified and documented (e.g. by the schedule network diagram).

4) Estimate Activity Durations: the time required to complete each identified activity, with estimated resources, must be estimated.

5) Develop Schedule: all activities durations and schedule constraints are analyzed in order to estimate completion time

6) Control Schedule: the status of project activities has to be monitored to update project progress and manage changes to the schedule baseline to achieve the plan.

To focus attention only on planning phases, authors refer only to steps from 2 to 5 of the previous list. In particular, applied methodologies included in steps 2 and 3 are coincident for both deterministic and probabilistic approaches. Instead, the application of methodologies belonging to steps 4 and 5 are specific for each approach. In the following sections, applied methods are detailed explained.

3.1 THE DETERMINISTIC APPROACH TAKEN AS REFERENCE

The easier approaches to get information about possible project duration are surely based on deterministic estimates. To estimate single activity duration, deterministic approaches are mainly used based on expert judgment, analogous and parametric estimations. According to the authors' own experience, they are applied by ETO manufacturing companies to get a first duration estimation for their projects even if few data are available. In the enterprise taken as reference, deterministic approaches are especially based on gained experience and on physical models.

Physical models are based on the correlation between activities intrinsic parameters and durations. They can be applied only on those activities whose duration is strictly dependent on few characteristic parameters (for example the cutting duration of the sheet depends on the thickness and the perimeter to be cut, the duration of the welding activity depends on the material density and the volume to be welded). In general, the duration (D_i) of the i^{th} the activity can be calculated through a physical model of the system, taking into account all the considered relevant quantities and also a certain level of productive efficiency.

Activities duration estimations, based on a statistical model, are valid for those activities for which physical models are not available, or it is not possible to have enough information to apply them. In these cases, it could be possible to identify a statistical model that allows linking the duration of the activity to one or more variables. Here, the correlation is considered significant only for Pearson correlation coefficient values $|r| \geq 0.7$.

Duration of the i^{th} activity, calculated in most cases through a univariate linear model that is identified through a regression analysis of historical data, could be inferred with an equation like (1):

$$D_i = a_i + b_i Y_i \quad (1)$$

where D_i is the duration, a_i and b_i are the coefficients of the regression line and Y_i is the independent variable.

Estimated values are used to compute the entire project duration. To get deterministic estimations, the CPM method is applied. The result provided by the deterministic method allows the enterprise to undertake some considerations about total durations and possible interventions to modify them.

3.2 SIMPLIFIED PROBABILISTIC APPROACH

The deterministic approach is suitable especially for projects whose activities are recurring and working conditions are stable. So, it is not appropriate to get accurate duration estimations of complex projects composed of many activities.

The proposed methodology pretends to outdo the typical weakness of the deterministic approach and get more accurate results. Often, ETO manufacturing is characterized by high innovation and one-of-a-kind productions. ETO companies can difficultly accurately manage their projects through common approaches. Uncertainties about completion times and the few information from the past make common and simplified approaches ineffective. Proposed simplification combines physical and statistical models used in the previously described method with PERT basics. In particular, the used method, called three-point estimation (Malcolm *et al.*, 1959), is applied to calculate the duration and variance of every single activity.

A probabilistic method needs some parameters to estimate expected, pessimistic and optimistic values. For this reason, the expected value and the variance of each duration are calculated.

Estimated data coming from previously described technique (deterministic approach) are considered as the most probable durations and have been enhanced with probabilistic variables provided by the addition of standard deviation of available data (Gallagher, 1987; Littlefield and Randolph, 1987).

As in PERT method, durations are considered as random variables with a Beta distribution probability density function (continuous and defined by two parameters α and β on the unit interval [0,1]), whose expected duration for the k_{th} activity, equal to μ_k, could be calculated using (2):

$$\mu_k = \frac{c_k + 4m_k + d_k}{6} \quad (2)$$

in which m_k represents the most probable value (D_i) for the duration of the activity (Gallagher, 1987; Littlefield and Randolph, 1987). To determine the most probable durations, the developed model proposes to use parametric (physical or statistical) estimations. For pessimistic (d_k) and optimistic (c_k) duration estimations, statistical approaches are used.

Still in the hypothesis of the validity of the Beta distribution, the variance σ_k^2 is represented by (3):

$$\sigma_k^2 = \frac{(d_k - c_k)^2}{36} \quad (3)$$

Comparing with the deterministic method, the probabilistic approach needs some further information to obtain pessimistic and optimistic values. For activities whose few or non-existent information about c_k and d_k are available, the following logic procedure is applied to calculate the respective values:

1. Results of some completed projects are taken as reference (when available), with details on the actual duration of the individual activities.

2. For all the projects, the most probable duration is calculated through parametric models, for each single k^{th} activity, using developed spreadsheets. For each k^{th} activity, whose

data are available from completed projects, the minimum duration is considered as the optimistic estimation (c_k) instead, the maximum duration is considered as the pessimistic one (d_k). For some activities, whose data are not available from completed orders, minimum and maximum durations are estimated consulting the operators.

3. After estimating all the activities durations, σ_k parameters are calculated to estimate σ parameter for each critical activity.

3.3 RESULTS COMPARISON

After estimating durations of each activity, the project duration is estimated. The method is applied to three different projects of the same company and after project completion, the results obtained from the scheduling are compared to the actual values. Comparisons between estimated and actual durations allow estimating method accuracy and highlight criticalities.

To estimate the duration of entire projects CPM is applied using deterministic duration for each activity. For probabilistic durations, once more, expected values are used to calculate critical path and project duration and their variance is added to results.

As already said, the deterministic method provides only one value for each estimation. The probabilistic method provides 3 values: optimistic, pessimistic and expected. For this reason, the comparison between actual, deterministic and probabilistic estimations can be done only using expected values from the last method.

To get information about the accuracy of the applied method, each activity estimation is compared with actual and results are provided in terms of percentage difference.

4 CASE STUDY

The case study for this work has been provided by a manufacturing enterprise operating in the production of mechanical parts. More in detail, the enterprise designs and produces high-pressure critical items applying ETO approach. These products are used for nuclear island construction and for space applications. It is specialized also in the manufacturing of tanks made of special alloys. The production concerns one-of-a-kind products of which a further specimen is hardly required. When produced components are part of large assemblies, especially for space projects, the deadline for products delivering must be accurately respected to not risk causing delays in much larger projects.

Summarizing, all project activities can be divided into two groups. The first group includes very common and recurrent activities whose durations are calculated using analogy technique. The second group includes all activities whose duration varies depending on many different parameters like parts size, working conditions, etc. Parametric estimations can be obtained by applying physical models or statistical ones.

According to PMI (see paragraph 3), step 2 requires activities definition. In this way, it is possible to define the list of all activities whose durations have to be estimated.

All analyzed projects are characterized by three phases: order reception and design, production, shipping.

The initial phase includes many activities, common to all 3 analyzed productions, from order acquisition to the arrival of the ordered materials. Activities belonging to this phase are (identifying letters of each activity are shown between square brackets):

- Project acquisition [A]. It is managed by a project office that accepts or rejects orders and defines other project aspects.
- Rough drawings and details drawings [B]. They belong to design activity.
- Development of Welding Book [C]. It is the preliminary scheduling of the welding phase.
- Inspection Test Plan redaction [D]. Definition of the set of inspections and checks necessary during the equipment manufacture.
- Sheet metal order [E]. It is based on the itemized list of components to the product.
- Forged metal order [F]. It is based on the itemized list of components to the product.
- Sheet metal reception [G].
- Forged metal reception [H].

For all of these, standard duration values consolidated over time are used to get estimates. Considering their fixed duration, they are not included in the comparisons between the obtained results.

The main phase includes several different activities which are listed below.

- Nozzles preparation [I]. This activity includes all the mechanical machining necessary to make nozzles ready to be assembled and welded to the tank.

- Non-destructive testing (NDT) [I, J, K, N, O, P, Q, R, S, T, U]. This activity includes various kinds of non-destructive tests and the duration depends on the type of required control.
- Bottom preparation [J]. This activity includes molding and edge banding of sheet metal (when necessary).
- Saddles preparation and welding [K]. Saddles are supports to be welded to the tank. Stress on these parts is due both to weight and inner pressure.
- Metal sheet cutting [L]. Sheet metal is cut, for every following use, through a numeric control laser cutter.
- Caulking [L]. This activity is important to prepare parts for successive welding processes. It is carried out, through numeric control laser cutters or milling machines (depends on metal thickness).
- Calendering [M]. It allows to get cylinders and truncated cone from plates.
- Welding [N, P, Q, R, S, T]. Many components are welded. The activity includes radial welding and longitudinal process both done through arc welding.
- Plating [O]. This treatment is done only on parts that get in touch with corrosive agents. It includes the deposition of plating material through the Weld Overlay process both simple and double.
- Assembling and welding [P]. Every tank has a specific accessory to increase security and specific functionality. Depending on specifications, an accessory can be assembled in different moments.

Durations of some of them are estimated using physical models, other through estimations. In particular, sufficient parameters are available to have a good estimation for sheet metal cutting, caulking, welding, plating, non-destructive testing, sandblasting and painting. For these, physical models are used. For calendaring, assembling, bottom preparation, nozzles preparation, saddles preparation and welding, data unavailability makes it necessary to resort to regression analysis.

The third phase includes:

- Post Weld Heat Treatment (PWHT) [U]. Welding is heat-treated to reduce residual stress.
- Hydrotest [V]. Products are tested to prevent potential pressure loss.
- Sandblasting and painting [W]. In this activity, different materials and components are prepared and painted through manual activity.
- Shipment [X]. Products are packed and shipped.

They are considered standard activities with fixed durations. They are not included in duration estimation.

The lack of availability of measured data on activities durations and the impossibility to get physical models for each project lead to a very simplified approach.

According to PMBOK, the third step of the implementation coincides with the organization of all activities in a list. List contains, for each activity, also information about preparatory ones. In **Table 2** all activities are collected and enhanced with the necessary information. Numbers between square brackets (as [1], [2], etc) are used to distinguish the mechanical machining done on different components.

All activities are organized into a flowchart after determining their sequence. Flowchart, with activities on nodes (AON) is represented in **Figure 1**.

Table 2 - List of analyzed activities with relative precedence

Activity	Index	Precedence
Project acquisition	A	/
Rough drawings and details drawings	B	A
Development of Welding Book	C	A
Inspection Test Plan redaction	D	A
Sheet metal order	E	A
Forged metal order	F	B
Sheet metal reception	G	E
Forged metal reception	H	F
Nozzles preparation + NDT	I	C, D, H
Bottom preparation + NDT	J	C, D, G
Saddles preparation + NDT	K	C, D, G
Cut + Caulking [1]	L	B, G
Calendering	M	L
Welding + NDT [1]	N	C, D, M
Plating + NDT [1]	O	N
Assembling + Welding + NDT	P	O
Welding + NDT [2]	Q	P
Welding + NDT [3]	R	I, J, N
Welding + NDT [4]	S	J, Q
Welding + NDT [5]	T	K, S
PWHT + NDT	U	R, T

Hydrotest	V	U
Sandblasting + painting	W	V
Shipment	X	

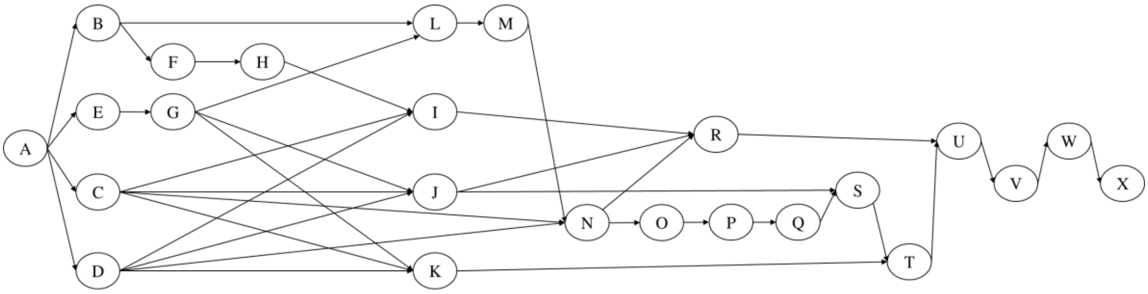

Figure 1 – Network diagram with activities on nodes (AON)

4.1 PROJECTS DURATION ESTIMATION THROUGH DETERMINISTIC APPROACH

The fourth step of PMBOK procedure establishes to estimate activities durations.

The used approach allows estimating each activity duration and later obtain a comparison between reached estimation and actual durations.

In **Table 3** all activities are collected. For each of them, the estimation method and the used parameters are specified.

As an example, a physical model for the estimation of cutting duration D_{cut} is reported in (4). In this case, the final product is a cut rectangular sheet to be calendered to obtain a cylinder.

Table 3 - List of analyzed activities, duration estimation method and used parameter for each estimation

Activity	Duration estimation	Used parameter
Nozzles preparation [I]	Regression	Considering the variability of manufacturing processes, it is not possible to get an accurate estimation. Linear regression has been applied correlating duration with nozzles mass.
Non-destructive testing [I, J, K, N, O, P, Q, R, S, T, U]	Physical model	The physical model is based on the previous plating duration. It is the only way to estimate duration.
Bottom preparation [J]	Regression	To estimate molding duration a linear regression between duration and sheet metal radius has been calculated.
Saddles preparation and welding [K]	Regression	Welding duration depends on the treatment and welding type. Regression has been done based on duration and parts mass.
Sheet metal cutting [L]	Physical model	It is possible to get estimates starting from cutting velocity. The physical model considers both cutting length and sheet thickness.
Caulking [L]	Physical model	It is possible to get estimates starting from working velocity. The model considers part length, sheet thickness and cutting velocity.
Calendering [M]	Regression	The duration of this activity is not related to part dimensions. Linear regression has been done correlating duration and parts thickness.
Welding [N, P, Q, R, S, T]	Physical model	Duration has been calculated through a physical model considering welding velocity, sheet thickness, and typology of process.
Plating [O]	Physical model	Duration has been estimated through a physical model depending on working speed, type of material deposition and part dimensions.

Assembly and welding [P]	Regression	Differences in size and form between parts make unavailable a possible physical model. The regression model correlates duration and parts mass.
Sandblasting and painting [W]	Physical model	Duration is estimated considering parts dimensions, deposited material, and process velocity.

$$D_{cut} = (1 + 0.3) \cdot \frac{2 \cdot \pi \cdot (d + 2 \cdot t) + 2 \cdot n \cdot H}{V \cdot 60} \qquad (4)$$

in (4) d represents the inner diameter of the cylinder, t is the thickness, n is the number of sheets, H is the height of the cylinder and V is the cutting velocity.

As already explained, statistical models are obtained through linear regression. About calendering, a linear regression between parts thickness and activity duration is carried out.

In **Figure 2** calendering activities durations, as a function of parts thickness, are collected with a regression line. In **Table 4** results of durations estimations of all activities of all three projects are collected.

Estimated durations obtained applying the deterministic approach are used to calculate the entire project duration through CPM analysis.

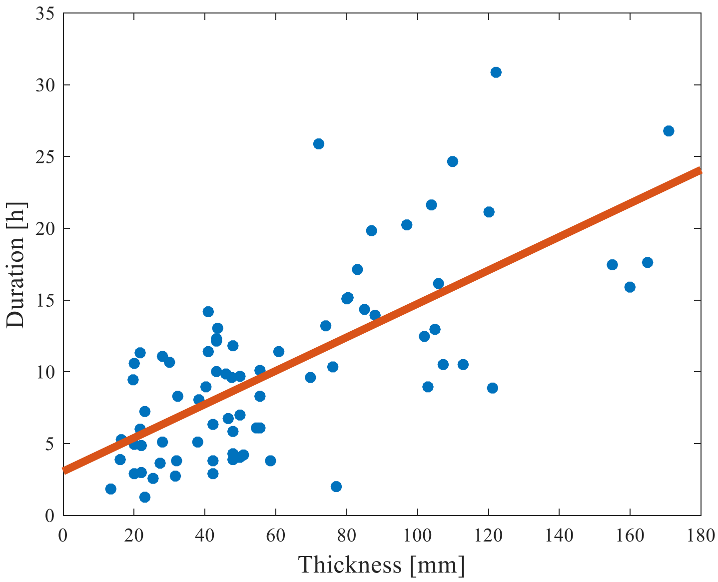

Figure 2 – Example of linear regression on calendering.

Table 4 – Results of deterministic estimations for all activities and projects

Activity	Index	Project 1 [d]	Project 2 [d]	Project 3 [d]
Nozzles preparation + NDT	I	9	14	9
Bottom preparation + NDT	J	24	16	15
Saddles preparation + NDT	K	2	15	2
Cut + Caulking [1]	L	8	18	5
Calendering	M	3	9	3
Welding + NDT [1]	N	9	14	4
Plating + NDT [1]	O	16	/	/
Assembling + Welding + NDT	P	49	141	33
Welding + NDT [2]	Q	13	61	6
Welding + NDT [3]	R	10	57	33
Welding + NDT [4]	S	5	4	4
Welding + NDT [5]	T	2	3	4
Sandblasting + painting	W	3	5	2
Entire project duration		231	490	182

For each node minimum and maximum durations are calculated from a developed network. In this way, the critical path is found out. The critical path is common for all three projects and it is composed of activities: A, E, G, L, M, N, O, P, Q, S, T, U, V, W, X (see **Table 2**). Durations of A, E, G, V, and X are considered fixed for all projects. L, M, N, O, P, Q, S, T, U and W are considered the only ones influencing project duration. Management of these is crucial. Any problem during critical activities could cause delays in the actual project. To consider a certain variance in probabilistic estimations central limit theorem is still considered valid, even if less than 30 activities are considered and a tolerable uncertainty is present. These considerations allow adding uncertainty intervals to each project duration. Entire projects durations are estimated with related confidence intervals from CPM application. In **Table 4** estimated project durations are collected.

To provide more detailed information about activities distribution, a Gantt chart (**Figure 3**) is implemented.

The same procedure is applied to all projects taken into account.

4.2 PROJECTS DURATION ESTIMATION TROUGH PROBABILISTIC METHOD

Al already explained in section 3, the probabilistic method is applied to all activities to obtain probabilistic estimations.

To estimate activities durations three-point method is used. To estimate the duration of entire projects CPM is applied with expected values.

The results of all duration estimations are collected in **Table 5**. Also, Gantt diagrams are implemented using expected durations. In this way, considering that expected durations have a probability of 50% it is possible to consider a buffer of time to add at the end of the project. The buffer size could be chosen based on the project riskiness.

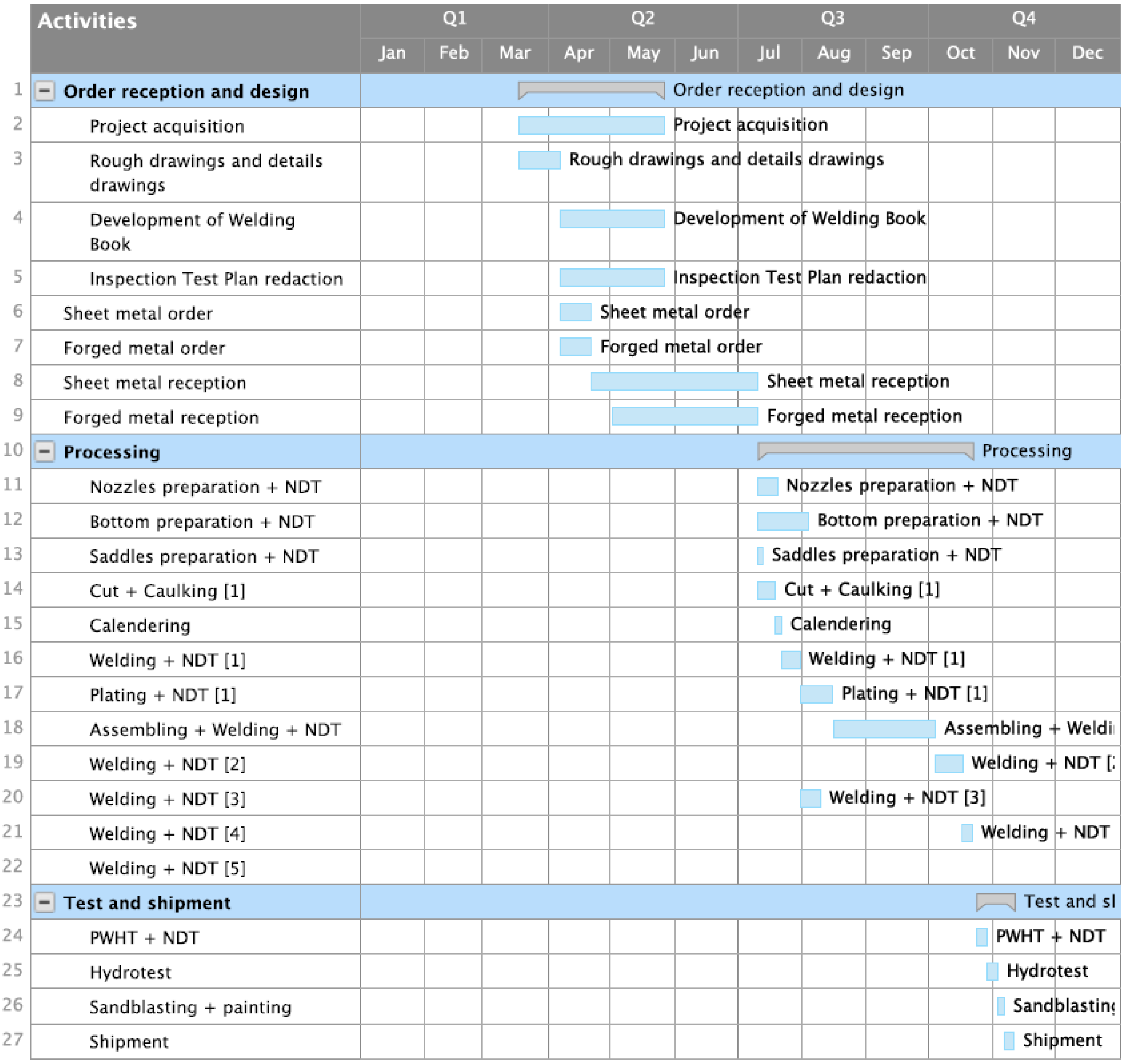

Figure 3 – Gantt chart of project 1 using probabilistic durations

Table 5 – Results of probabilistic estimations for all activities and projects

Activity	Index	Project 1		Project 2		Project 3	
		Exp. [d]	σ [d]	Exp. [d]	σ [d]	Exp. [d]	σ [d]
Nozzles preparation + NDT	I	11	3	14	3	11	3
Bottom preparation + NDT	J	24	4	16	2	15	2
Saddles preparation + NDT	K	2	1	15	2	2	1
Cut + Caulking [1]	L	8	1	18	2	5	1
Calendering	M	4	2	11	4	3	1
Welding + NDT [1]	N	9	1	14	2	4	1
Plating + NDT [1]	O	16	2	/	/	/	/
Assembling + Welding + NDT	P	62	20	123	20	51	20
Welding + NDT [2]	Q	13	2	62	6	6	1
Welding + NDT [3]	R	10	1	58	5	33	3
Welding + NDT [4]	S	5	1	4	1	4	1
Welding + NDT [5]	T	2	1	3	1	4	1
Sandblasting + painting	W	3	1	11	1	2	1
Entire project duration		252	20	491	22	204	20

4.3 COMPARISON BETWEEN ESTIMATED AND ACTUAL DURATIONS

Achieved estimations are compared with actual durations. Therefore, only the expected values are considered to evaluate the differences between estimated deterministic durations and the three-point method application. This restriction is necessary because of the unavailability of further values from the deterministic method. Results of deviations between actual durations (taken as reference) and estimated values of all considered activities for both deterministic approach (Det) and simplified statistical approach (3Pt) are collected in **Table 6**. Some activities, regarding the same part, are collected in one general activity.

In **Figure 4** are reported duration intervals provided by the probabilistic approach (using 3σ confidence interval), provided by a deterministic approach and actual one. It is important to note that for all three projects taken into account actual durations are within the confidence intervals.

5 DISCUSSION

Results in **Table 6** show that expected durations estimated with the probabilistic method have, in general, shorter durations than the previously used method. This aspect can be due to typical PERT behavior which, as already described, tends to underestimate activities durations.

The three-point method could partially outdo the deterministic method, providing probabilistic distribution in addition to the specified expected value. Calculated uncertainty can be positively used to estimate activities durations considering also a time reserve to add to the project.

Table 6 – Comparison between expected estimated durations (days) of each activity and actual ones

Activity	**Index**	Δ_{PROJ1} [%]		Δ_{PROJ2} [%]		Δ_{PROJ3} [%]		$\bar{\Delta}$ [%]	
		Det.	**3Pt**	**Det.**	**3Pt**	**Det.**	**3Pt**	**Det.**	**3Pt**
Nozzles preparation + NDT	I	30.8	15.4	12.5	12.5	-50	-83.3	-2.2	-18.5
Bottom preparation	J	14.3	14.3	42.9	46.5	-36.4	-36.4	6.9	8.1
Saddles preparation	K	50	50	25	25	0	0	25	25
Cut + Caulking [1]	L	0	0	35.7	35.7	-25	-25	83.9	3.6
Calendering	M	40	20	10	-10	-50	-50	0	-13.3
Welding + NDT [1]	N	43.8	43.8	33.3	33.3	60	60	45.7	45.7
Plating + NDT [1]	O	15.8	15.8	/	/	/	/	15.8	15.8
Assembling + Welding + NDT	P	38.8	22.5	31.2	40	-73.7	-168.4	-1.2	-35.3
Welding + NDT [2]	Q	13.3	13.3	12.9	12.9	40	40	22.1	22.1
Welding + NDT [3]	R	23.1	23.1	9.5	9.5	-10	-10	7.5	7.5
Welding + NDT [4]	S	0	0	-33.3	-33.3	20	20	-4,4	-4.4
Welding + NDT [5]	T	0	0	50	50	20	20	23.3	23.3
Sandblasting + painting	W	0	0	72.2	72.2	33.3	33.3	35.2	35.2

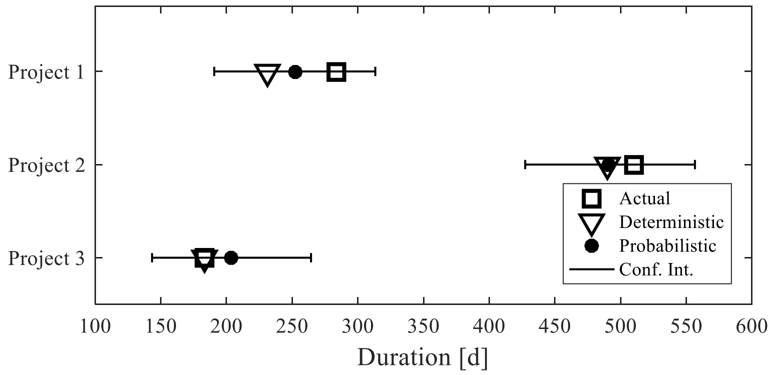

Figure 4 – Comparison between actual projects durations and estimated values

Thus, it is possible to forecast project duration both using expected values and pessimistic ones. It is important to note that for some of the considered activities, the number of available duration samples is not sufficient to have the necessary significance. Nevertheless, considering the practical point of view, obtained results are useful to get more information about projects duration than the reference method.

Enterprise can decide which value taking into consideration based on the perception of the risk to estimate the whole project duration. Using the expected or a value shifted towards the optimistic, the enterprise considers that the risk of possible delays could below. Quite the opposite, if the enterprise takes into account pessimistic estimation, it considers the project very risky. Enterprise can also operate on entire project duration considering total duration equal to the expected estimate plus a time buffer (eventually up to pessimistic estimate). In this last case, the result is an overall estimate which could still protect the enterprise at least as regards the time aspect (it is clear that for the cost aspect it would be more important to understand which activities will verify the deviation).

These possibilities make necessary control activities on project execution. An accurate control can help the project manager to check the progress of the work and possibly establish new resource allocation to vary actual duration.

Considering only expected durations of entire projects, the comparison in **Table 5** shows that in 2 cases developed method leads to better results. The result is worse than deterministic estimation because of an overestimation in project 2. As already explained, the analysis of single activity estimation does not make sense because of the scarce availability of data and information. However, this kind of application leads to better duration estimations and, considering the 3σ intervals, all the production durations are well estimated. In the end, reducing confidence interval from 3σ to 2σ, actual durations of all projects are within the range, only reducing the interval to σ one of 3 duration estimations is out of the limit.

6 CONCLUSIONS

In this paper, the authors propose an application of a simplified probabilistic methodology for estimating the duration of manufacturing projects in ETO companies.

Through the application of the methodology to three different projects related to the same case study, the authors show the potential benefits of the adoption of a probabilistic approach instead of a traditional deterministic one.

Results demonstrate how the deterministic approach often leads to significant estimation errors that cause problems in resource management and customer satisfaction. The simplified probabilistic approach requires some more data and some more complex calculations, but it is able to estimate the time interval in which the actual duration of the project will fall. In this way, the enterprise could be able to schedule project activities considering their expected durations and to estimate, in an easy way, a time reserve capable of effectively mitigating the risk of delaying the completion of the project.

This study refers to a specific case study, but schedule planning dynamics described are common to many other ETO contexts and the authors believe that lessons learned from their case study can be used to better understand and improve the schedule planning process in other companies or in other similar sectors.

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