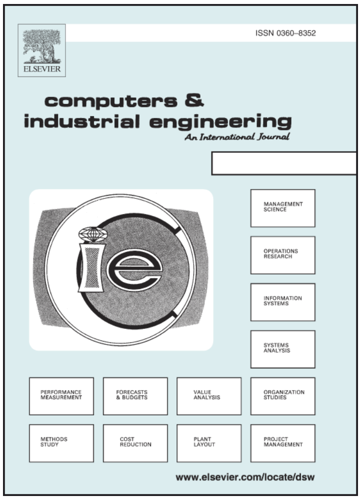

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# Time Cost Quality Trade-off Problems : a survey exploring the assessment of quality

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# Time Cost Quality Trade-off Problems: a survey exploring the assessment of quality

## Abstract

Time Cost Trade-off Problems have received considerable attention in the literature on deterministic project scheduling problems but integrating the quality factor to these problems dates back to the mid-nineties with the pioneering work of Babu and Suresh (1996). Since then, to the best of our knowledge, about twenty papers have been published on this topic. The present paper analyses these Time Cost Quality Trade-off Problems in light of the usual classification for Time Cost Trade-off Problems that is based upon the number and category of resources and on the continuous or discrete type of the relationship between duration and cost or resources utilisation. In this survey, the emphasis is on the definition of project activities quality and on aggregation methods used to derive the overall project quality. We report the absence of a direct relationship between quality and resources allocated to activities and a lack of use of the lexicographic method to solve the problem.

*Keywords:* Time Cost Quality Trade-off Problems; project scheduling; project crashing; activity quality; project quality

## 1. Introduction

The core strategy to faster product development projects so as to gain competitive advantage consists in overlapping development stages so the downstream stage can start earlier by using preliminary information. Quality issues implied by overlapping are resolved using rework to correct design flaws resulting from partial information. Thus for such projects, quality is implicitly taken into account with rework (see for instance Lin et al., 2010 for a recent contribution). Besides, to accelerate non innovative projects so as to ensure delivery on the planned date, some of the project activities can be completed faster than normal by either spending less time on them or more money to cover the expenses of additional resources allotted to them. Thus accelerating a project increases its cost. As it is commonly assumed that shortening the duration of activities decreases their quality and consequently the project quality, there is a trade-off between time, cost and quality. Most of Time Cost Quality Trade-off Problems (TCQTP) are modelled in a similar way to Time Cost Trade-off Problems (TCTP) that have been extensively studied in the literature related to deterministic project scheduling (see Weglarz et al., 2011 for a recent survey). As such, they share common assumptions that we discuss in this survey to provide a grid for classifying TCQTP. In TCQTP studied here, quality of any activity is measured by an indicator varying between 0 and 1 and so is the overall project quality for it is defined as a function of quality levels attained by individual activities. We analyse the meaning of such an indicator, its acceptable level as well as aggregation methods used to derive the project quality.

The remainder of this paper is organised as follows. Section 2 discusses the definition and measure of quality and analyses the impact of acceleration on quality. Section 3 provides a classification of TCQTP based upon modelling assumptions and solution methods, which eventually led us to identify three main approaches. In the first one, quality is implicitly assessed through rework needed to correct non conforming activities (Section 4). In the second one, the quality of any activity is expressed as a continuous function of its duration and cost (Section 5). In the last group of references, quality of an activity is estimated in each of its possible execution modes, a mode corresponding to a specific combination of resources to process the activity with an associated duration and cost. Section 7 provides a summary of the contributions in terms of resource category, activity quality and project quality definitions, solution approaches and project instances being addressed.

## 2. Definition and measure of quality and impact of acceleration

Garvin (1984) proposes several dimensions of quality from which we select conformance (match with specifications) as opposed to perceived quality which is the most subjective dimension. Conformance makes quality a measure variable whereas perceived quality is a useful concept in the early design stages of a new product. As an example, smell intensity of car interior is a component of perceived quality. A thorough analysis of perceived quality may be found in Stylidis et al. (2015). For non innovative projects that are under the scope of this survey, quality as conformance to customer specifications and to technical requirements is the relevant definition. Customer specifications involve requirements related to aesthetics (fits and finishes) or to the utilisation of high quality components and raw materials to ensure a longer product life. These specifications may be changed to lower requirements to shorten the project duration. Conversely, technical requirements can hardly be modified for they guarantee product functionality, environmental constraints satisfaction and a level of excellence set by the company.

Consider for instance the paint activity in a manufacturing project such as a high speed train. Some flaws are acceptable whereas others are not. Mandatory technical requirements include, amongst others, compliance with a specific chemical composition of the paint to fulfil environmental requirements or compliance with pre-determined paint zones. If a visible paint zone is not respected, the company will decide for a rework since the aesthetic of the train is critical to its image of excellence even if this flaw does not question the product functionality or its durability. Conversely a slight hue defect may be considered as acceptable for the company but not for the customer unless he is willing to downgrade his requirements to save time on the project duration. In such a case quality will be below its maximum level.

Quality of an activity can therefore be measured as a percentage of the checked items in its quality control inspection checklist (see for instance Mohammadipour and Sadjadi, 2016; Fu and Zhang, 2016; Babu and Suresh, 1996 and Khang and Myint, 1999). The highest possible quality is equal to one meaning that 100% of the items are checked and may be reached primarily in normal production conditions where the project is not accelerated or said to be executed in a normal mode which corresponds to the minimum resource allocation (Weglarz et al., 2011).

A minimum level for an activity quality may correspond to the proportion of unacceptable flaws in its checklist. Thus, imposing such a minimum quality level on activities would allow for acceleration without rework, on average. However in all papers tackling TCQTP but one, a minimum level is required for the project quality only, which is mostly defined as the average of qualities of its activities. Such an aggregation may imply that the project quality can attain the required level with unacceptable qualities for some of the project activities. It should be noted that when no flaw is tolerated then the evaluation of the quality is binary and rework is mandatory if quality does not reach its maximum level.

There is a need to expedite a project if its normal finish date does not meet the completion date desired by the customer or if random events cause the project to fall behind schedule or when there are financial incentives to finish the project ahead of schedule. This implies completing some of the activities faster than normal by allocating additional resources such as overtime, temporary workers or more powerful equipments. Thus accelerating an activity saves time but increases costs. Besides, duration reduction negatively impacts quality because acceleration requires almost always additional manpower, unless in fully automatised production processes, which are far from representing the majority of manufacturing systems in practice. If a single additional resource like overtime is used to accelerate, then quality of an activity may be expressed as an increasing continuous function of duration since (*i*) overtime hours are continuously divisible and each amount of overtime leads to a specific duration; (*ii*) higher duration reductions are achieved with more overtime and lower quality levels because an intensive use of overtime implies fatigue and a motivation decrease that negatively affect quality (see Li et al., 2000). In a lot of real applications, resources are discretely divisible like machines, tools and workers so a project can be accelerated by combining for each activity different amounts of such heterogenous resources leading to several discrete execution modes to which correspond a duration, a cost of these resources and a quality of the activity. Again, the quality of an activity decreases with duration reduction due to the use of overtime or temporary workers who crowd the workplace, which can be deleterious to quality (Li et al., 2000).

## 3. Typology of Time Cost Quality Trade-off Problems

In the last five decades, there has been a great deal of research on project management and scheduling with the aim at modelling adequately practical problems, and developing efficient solution approaches. The focus here is on scheduling a single project (as opposed to simultaneously scheduling multiple projects) where the project is defined as a collection of non preemptable activities with precedence relationships. The main objective is to minimise the project completion time subject to a budget constraint or to resource constraints in a deterministic environment. Weglarz et al. (2011) survey Time Cost Trade-off Problems and propose a typology based on assumptions on the number of resources (single versus multiple) and on their category (continuous or discrete; renewable or not), as well as on objectives (single versus multiple) and solution approaches (exact or heuristic). As Time Cost Quality Trade-off problems in the literature follow same assumptions, it is important to classify them according to this typology so as to outline the problem type being addressed. Thus, we first study how the quality factor is integrated in Time Cost Trade-off Problems and which solution approaches have been implemented (Section 3.1). We then analyse how quality of an activity is modelled in these problems (Section 3.2).

### *3.1. Integrating quality in Time Cost Trade-off Problems and solution approaches*

A typology of Time Cost Trade-off Problems can be based on the number and category of resources as well as on the type of relationship between duration and resources as shown in Figure 1. If a single renewable resource is considered such as manpower or equipment, we face Time Resource Trade-off Problems (TRTP) where the duration of an activity is assumed to be a non increasing function of the amount of the renewable resource. When this function is continuous, we get Continuous Time Resource Trade-off Problems (CTRTP). Conversely, if this function is discrete we obtain Discrete Time Resource Trade-off Problems (DTRTP) in which any activity can be executed according to several processing modes where a mode represents a possible allocation of the resource with a corresponding duration. As can be seen in Figure 1, quality has never been integrated in Time Resource Trade-off Problems.

Energy, money or raw materials are examples of single non renewable resources. But in the literature, only money is actually considered as the single non renewable resource and corresponds to the cost of any category of resources, which leads to Time Cost Trade-off Problems (TCTP). For instance money as the non renewable resource can be the cost of overtime, which is a single renewable resource, or the cost of several renewable and non renewable resources defined as the money spent for instance on components, equipments and manpower. In such Time Cost Trade-off Problems, the cost of any activity is a non increasing function of its duration. This function can either be continuous (Continuous Time Cost Trade-off Problems, CTCTP), or discrete (Discrete Time Cost Trade-off Problems, DTCTP). Three references introduce the quality in CTCTP (Babu and Suresh, 1996; Khang and Myint, 1999; Zhang et al., 2014). No less than ten references consider the quality in DTCTP where each activity can be processed in one mode amongst several execution modes, a mode corresponding to a combination of cost, duration and quality (Tran et al., 2015; Kim et al., 2012; Liberatore and Pollack-Jonhson, 2013; Tareghian and Taheri, 2006 and 2007; Mohammadipour and Sadjadi, 2016; El-Rayes and Kandil, 2005; Mungle et al., 2013; Monghasemi et al., 2015; Afshar et al., 2007).

If several renewable resources are utilised and the duration of an activity is a non increasing discrete function of the amount of resources allocated to its execution, we obtain Multiple Discrete Time Cost Trade-off Problems (MDTRTP) in which the quality

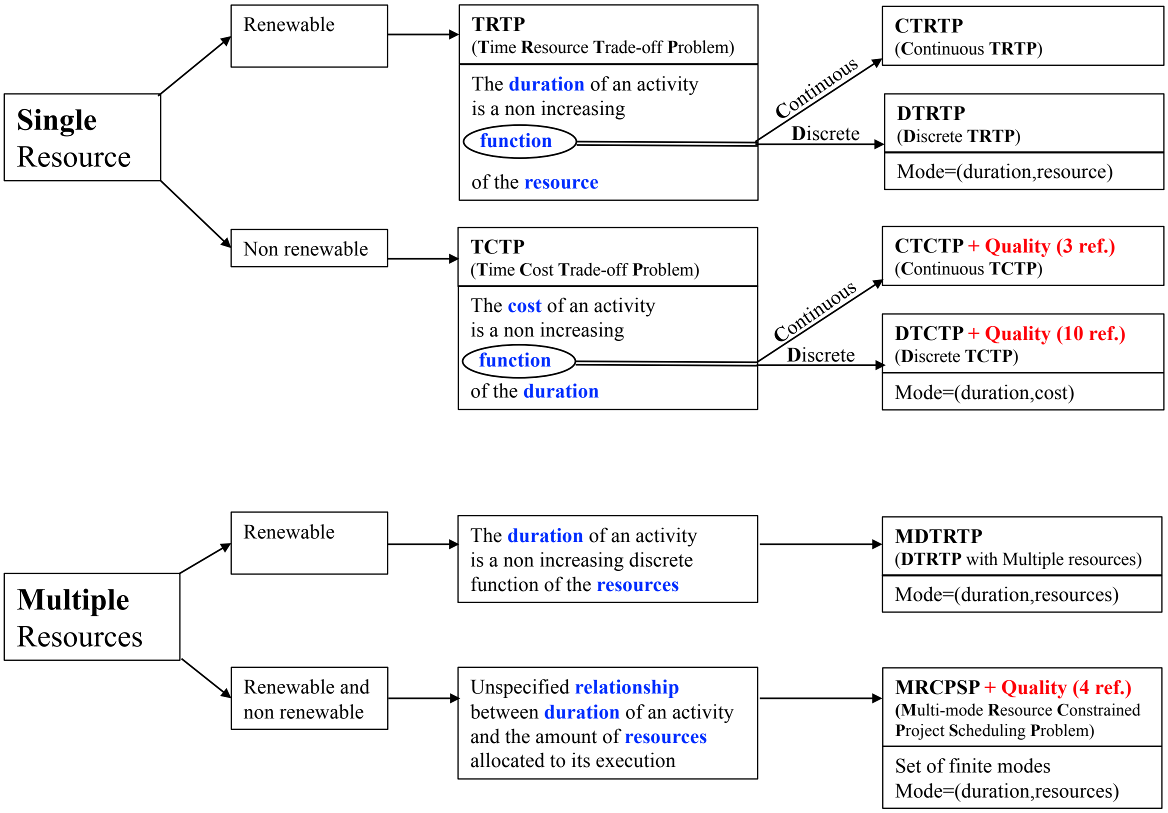

Figure 1: Classification of Time Resource or Cost Trade-off Problems with quality

issue has never been considered in the literature. Conversely we found four references dealing with quality in Multi mode Resource Constrained Project Scheduling Problems (MRCPSP) that include renewable and/or non renewable resources and for which the Resource Constrained Project Scheduling Problem (RCPSP) is a special case as there is a single execution mode (Icmeli-Tukel and Rom, 1997; Tiwari et al., 2009; Fu and Zhang, 2016; Afruzi et al., 2014).

Several objectives, formulations and solution methods are considered in the literature, as shown in Figure 2.

If the assessment of quality is binary, the objective is to minimise the rework cost or the rework duration. Otherwise, the objective is to minimise the project duration or its cost or to maximise the project quality as an aggregation of individual qualities (namely qualities of activities), the arithmetic mean being quite often used. Single objective formulations are most common and include one objective amongst the five aforementioned ones or make use of scalarisation approaches. In most references the problem is solved to optimality using linear optimisation techniques or non linear ones when the project quality is a geometric mean of activities quality (8 papers). Population-based metaheuristics are marginally adopted to solve the problem heuristically (3 contributions).

Multi-objective approaches (6 references) only tackle Discrete Time Cost Quality Trade-off Problems (DTCQTP). The problem is to select an execution mode for each

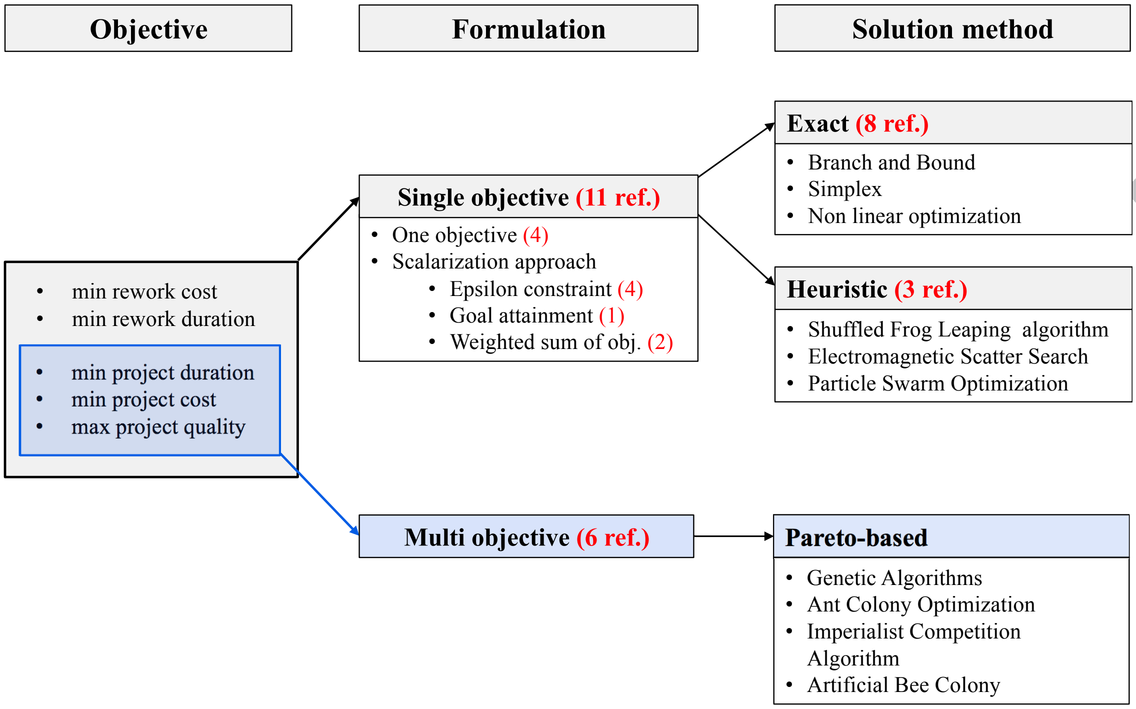

Figure 2: Formulations and solution methods

activity so as to reach the best compromises among time, cost, and quality for the project. All the contributions adopt Pareto-based evolutionary algorithms such as Multi-Objective Genetic Algorithms or Multi-Objective Ant Colony Optimisation.

### *3.2. Quality modelling*

Combining the objectives of the contributions with the modelling aspects of TCQTP as discussed in Section 3.1, we propose to classify the references in three groups. The first group includes the models integrating implicitly quality with rework. The second group involves contributions that model the quality of an activity as a continuous function of its duration only or of its duration and cost. The last group of references assumes that the quality is an estimated parameter in each execution mode. Based on this typology, the next sections review these contributions that we also summarise in Table 1 in terms of model class; resource category; cost and quality of an activity; aggregation method for the project quality; objectives and decision variables; mathematical formulation and solution method; maximum number of activities in the instances to which the solution method was applied and project type, indicating if it is real case based or not.

| **Rework as an implicit assessment of quality** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Contribution** | **Model class** | **Resource category** | **Activity cost** | **Activity quality** | **Project quality** | **Objective(s)** | **Decision variables** | **Formulation / Solution method** | **Instance max. size** | **Project type** |
| Icmeli-Tukel and Rom (1997) | RCPSP | Multiple, renewable | Rework cost = overtime cost | Binary assessment (conformance or not). Quality is estimated through rework cost | -- | Single objective: min. weighted sum of proportion of rework time and cost | Binaries for completion date; Continuous proportions of the total rework time and cost used | MILP / Exact | 32 | Random (PROGEN, problem generator by Kolisch et al., 1995) |
| Kim et al. (2012) | DTCTP | Single, non renewable | Estimated in each mode | Binary assessment (conformance or not). Quality is estimated through Potential Quality Loss Cost | -- | Single objective: min. crash times and non conformance risk activities | Integers for activities duration; Binaries to select non conformance risk activities | MILP / Exact | 18 | Robot type palletising system installation (real case based) |
| Tiwari et al. (2009) | MRCPSP | Multiple, renewable | Rework cost | Binary assessment | -- | Single objective: min. project makespan | Binaries for activities execution mode and finish time; Binaries for mode selection for rework and finish time | 0-1 ILP / Exact | 40<br>14 | Random<br>Course development (real case based) |
| **Quality as a continuous function of duration and cost** | | | | | | | | | | |
| **Contribution** | **Model class** | **Resource category** | **Activity cost** | **Activity quality** | **Project quality** | **Objective(s)** | **Decision variables** | **Formulation / Solution method** | **Instance max. size** | **Project type** |
| Babu and Suresh (1996) | CTCTP + Quality | Single, non renewable | Linear decreasing function of duration | Linear increasing function of **duration** | Arithmetic and geometric mean of individual qualities | Single objective: min. project makespan or min. project cost or max. project quality | Continuous variables for activities finish time | Continuous linear and non linear program; Epsilon-constraint / Exact | 14 | Example |
| Khang and Myint (1999) | CTCTP + Quality | Single, non renewable (overtime cost) | Linear decreasing function of duration | Linear increasing function of **duration** | Arithmetic and geometric mean of individual qualities | Single objective: min. project makespan; min. project cost; max. project quality | Continuous variables for activities start time and duration | Continuous linear and non linear program; Epsilon-constraint / Exact | 52 | Pre-heater tower of a cement factory (real case based) |
| Zhang et al. (2014) | CTCTP + Quality | Single, non renewable | Quadratic function of duration | Quadratic function of **duration** | Arithmetic mean of individual qualities | Single objective: min. weighted sum of cost, duration and quality variations compared to contractual values | Continuous variables for activities duration | Continuous non linear program / Metaheuristic (Immune Genetic Particle Swarm Optimisation) | 19 | Three-floor office building example |
| Tran et al. (2015) | DTCTP + Quality | Single, non renewable | Linear decreasing function of duration | Quadratic function of **duration** | Arithmetic mean of individual qualities | Multi-objective: min. project makespan and min. project cost and max. project quality | Continuous variables for activities duration | Continuous non linear program / Metaheuristic (Hybrid Multiple Objective Artificial Bee Colony with Differential Evolution: MO-ABC-DE) | 60 | Construction (random) |
| Liberatore and Pollack-Johnson (2013) | DTCTP + Quality | Single, non renewable | | Non linear function of **duration and cost** | Minimum of individual qualities | Single objective: max. project quality | Continuous variables for activities cost and finish time | Continuous non linear program / Exact | 7<br>2 | Software development<br>Translation (real cases based) |
| Fu and Zhang (2016) | MRCPSP + Quality | Multiple, renewable and non renewable | Prevention cost and rework cost, direct cost is a linear decreasing function of duration | Non linear function of **duration and cost** | Cumulative quality as a discrete function of activities quality in a group | Single objective: min. project cost | Binaries for activities execution mode and start time; Binaries for repair work and start time | Binary non-linear program/ Metaheuristic (Shuffled Frog-Leaping Algorithm: SFLA) | 16 | Framed railway overpass |
| **Quality as an estimated parameter in each execution mode** | | | | | | | | | | |
| **Contribution** | **Model class** | **Resource category** | **Activity cost** | **Activity quality** | **Project quality** | **Objective(s)** | **Decision variables** | **Formulation / Solution method** | **Instance max. size** | **Project type** |
| Tareghian and Taheri (2006) | DTCTP + Quality | Single, non renewable | Estimated in each mode, decreasing with duration | Estimated in each mode | Arithmetic and geometric mean of individual qualities | Single objective: min. project makespan or min. project cost or max. project quality | Discrete variables for activities finish time; Binaries for activities execution mode | Integer linear and non linear program; Epsilon-constraint / Exact | 45 | Random (DAGEN, problem generator by Agrawal et al., 1996) |
| Tareghian and Taheri (2007) | DTCTP + Quality | Single, non renewable | Estimated in each mode, decreasing with duration | Estimated in each mode | Geometric mean of individual qualities | Single objective: min. project makespan or min. project cost or max. project quality | Binaries for finish time in t; Binaries for activities execution mode | 0-1 non linear program; Epsilon-constraint / Metaheuristic (Electromagnetic Scatter Search) | 20000 | Random |
| Mohammadipour and Sadjadi (2016) | DTCTP + Quality | Single, non renewable | Estimated cost associated with duration reduction | Estimated quality associated with duration reduction | Sum of individual qualities decrease | Single objective: min. project cost or min. risk or min. project quality decrease | Binaries for reduced time of t periods; Continuous variables for start and finish times | MILP; Goal Attainment / Exact | 18 | Two-story building example |
| Afruzi et al. (2014) | MRCPSP + Quality | Multiple, renewable | Cost of resources utilised in each mode | Estimated in each mode | Weighted mean of individual qualities | Multi-objective: min. project makespan and min. project cost and max. project quality | Binaries for crashing; Binaries for activities execution mode | 0-1 linear program / Metaheuristic (Multi-Objective Imperialist Competitive Algorithm: MOICA) | 31 | Random (PSPLIB, a library of projects by Kolisch and Sprecher, 1997) |
| El-Rayes and Kandil (2005) | DTCTP + Quality | Multiple, renewable and non renewable resources aggregated through a cost in each mode | Estimated in each mode | Estimated in each mode as a weighted sum of measurable quality indicators | Weighted mean of individual qualities | Multi-objective: min. project makespan and min. project cost and max. project quality | Binaries for activities execution mode | 0-1 linear program / Metaheuristic (Multi-Objective Genetic Algorithm: NSGAII) | 18 | Highway construction (real case based) |
| Mungle et al. (2013) | DTCTP + Quality | Single, non renewable | Cost of subcontracting and tardiness penalty cost in each mode (subcontracting option) | Estimated in each mode as a weighted sum of measurable quality indicators | Weighted sum of minimum and average of individual qualities | Multi-objective: min. project makespan and min. project cost and max. project quality | Binaries for activities subcontracting options | 0-1 linear program / Metaheuristic (Fuzzy Clustering-Based Genetic Algorithm: FCGA) | 18 | Highway construction (real case based) |
| Monghasemi et al. (2015) | DTCTP + Quality | Single, non renewable | Cost of subcontracting and tardiness penalty cost in each mode (subcontracting option) | Estimated in each mode as a weighted sum of measurable quality indicators | Weighted sum of minimum and average of individual qualities | Multi-objective: min. project makespan and min. project cost and max. project quality | Binaries for activities execution mode | 0-1 non linear program / Metaheuristic (Multi-Objective Genetic Algorithm: NSGAII) | 18 | Highway construction (real case based) |
| Afshar et al. (2007) | DTCTP + Quality | Multiple, renewable and non renewable resources aggregated through a cost in each mode | direct and indirect cost estimated in each mode | Estimated in each mode as a weighted sum of measurable quality indicators | Weighted mean of individual qualities | Multi-objective: min. project makespan and min. project cost and max. project quality | Binaries for activities execution mode | 0-1 linear program / Metaheuristic (Multi-Objective Ant Colony Optimisation: MOACO) | 7 | Example |

Table 1: Summary of contributions

## 4. Rework as an implicit assessment of quality

To the best of our knowledge, only three references deal with rework as an implicit assessment of quality in non innovative projects whereas rework is extensively addressed in the literature related to product development projects (see for instance Dheghan et al., 2015 for a short survey). In these models, the evaluation of quality can be considered as binary: if an activity does not fit all of the requirements, rework is needed. The objective is therefore to minimise rework cost or rework duration or a combination of both. The limit of such approaches relies on the absence of a tolerance to flaws although in practice a lot of minor flaws can be accepted. The authors simply argue that most of the projects have at least one non conforming activity needing rework.

In the model developed by Icmeli-Tukel and Rom (1997) the objective is to maximise the quality of a project by minimising the sum of the proportion of the total rework time used and the corresponding proportion of additional rework cost used that includes overtime costs. The quality of a project is therefore measured by the time and cost necessary for reworking the activities that do not meet specifications. Rework cost is an increasing function of rework times and rework time increases with the number of predecessors of an activity. Rework time and costs are estimated parameters and are higher for activities completed later in the project. Several resources are available in limited quantity and each activity requires some units of each resource. The problem is formulated as a traditional RCPSP except for the objective function and consists in determining the completion time of activities so as to minimise the total rework time and cost subject to precedence constraints, to a maximum budget and to resource availabilities. In a first formulation completion times are integers whereas this integrality constraint is relaxed in a second formulation. Both linear models are applied to 110 instances generated at random using PROGEN, a problem generator developed by Kolisch et al. (1995), with 32 activities and 4 resources per instance and several parameters values for rework times and costs. Optimal solutions were obtained for most problems in a fast computation time. From a practical standpoint, implementing this approach would require a great deal of work in estimating rework cost and time for any completion time or for carefully chosen time intervals. Furthermore, using a sum of rework time and cost as the objective function with equal weights is questionable in terms of decision makers' preferences.

Kim et al. (2012) consider an acceleration strategy with a single non renewable resource where each activity can be executed in a normal mode or in a crash mode (maximum allocation of resource), leading to a DTCTP with two execution modes per activity. If any of the project activities does not satisfy the requirements due to crashing, rework may be necessary with an associated time and cost. The authors propose a mixed integer linear programming model where the objective is to minimise the total Potential Quality Loss Cost (PQLC) associated with rework and direct costs that depend on activities duration. Decision variables are activities duration and binary variables to express the execution mode (crash or normal). If an activity is crashed, a PQLC is incurred and represents the cost of corrective actions to make acceptable the activity quality. The problem is therefore to determine which activities are to be crashed so as to minimise direct costs and PQLC subject to a deadline and precedence constraints as well as a limit on the number of crashed activities to reach an acceptable non conformance risk for the project. The model is applied to a robot type palletising system with 18 activities and successfully solved to optimality. Practical implementation of such a model implies the estimation of PQLC.

Tiwari et al. (2009) consider multiple constrained resources and several executions modes for each activity requiring renewable and non renewable resources (MRCPSP). They assume heterogenous skill levels among renewable resources in a given resource pool for modelling a labor assignment problem in a company's customers training course project. Each activity can be executed in several modes corresponding to the use of a worker with a specific skill level. If a less effective individual is initially assigned to the activity thus rework is needed and must be handled by a higher skilled level. No rework is required if a high skilled worker is initially assigned to the activity but this worker will be committed to the activity for a longer time than the rework time. Again quality is binary and is therefore implicitly taken into account through rework. The problem consists in selecting initial execution modes and rework modes if needed so as to minimise the project duration under precedence constraints and resource availabilities, each activity requiring a specific quantity of each resource in each mode. The problem is formulated as a 0-1 linear program and solved to optimality for several randomly generated projects obtained by varying the number of activities (up to 40) and the number of initial execution modes and rework modes. The model is also applied to a real course development project in a telecommunication company with 14 activities and 17 workers leading to 17 initial execution modes for completing an activity.

## 5. Quality as a continuous function of duration and cost

In this section, quality is expressed as a continuous decreasing function of duration only (Section 5.1). The use of overtime to accelerate a project may support this statement as overtime implies fatigue which impacts quality. Quality is also assumed to be dependent not only on duration but also on the amount of money (cost) dedicated to the execution of an activity since spending more is assumed to increase quality (Section 5.2).

### *5.1. Quality as a function of duration only*

Amongst the four contributions we analyse here, the first two ones assume the cost and quality of an activity to be linear with its duration. This means that the marginal productivity is constant and the marginal quality loss related to each unit time of duration reduction is also constant. These assumptions can be restrictive in practice and are relaxed in the last two references that consider diminishing marginal productivity and increasing marginal quality loss.

### *5.1.1. Quality as a linear increasing function of duration*

To the best of our knowledge, Babu and Suresh (1996) are the first authors who model the impact of acceleration on quality where the cost of any activity is an affine function of its duration and bounded by its crashed duration and cost (maximum resource allocation) and by its normal duration and cost, these four parameters being estimated by experts. Similarly, the quality of an activity is an affine function of its duration and normal and crashed quality parameters are also assumed to be estimated by experts. The authors adopt a scalarisation approach using the epsilon constraint method where a single objective function is optimised whereas the other objectives are expressed as constraints. Thus a first optimisation program is to minimise the project completion time under a budget constraint and the project quality defined as the sum of individual qualities must reach a given threshold. In a second program, the project total cost is minimised under a deadline constraint and a minimum level for the project quality. The last program maximises the project quality under a deadline constraint and a budget constraint. To compute the project quality, the geometric mean of activities quality is also used for it is relevant when individual qualities are dispersed. Additionally, the project quality is defined as the minimum of activities quality for a project can be viewed as an integrated set of activities so its quality can be assumed to be only as high as its weakest activity quality. These programming models are applied to an illustrative example of a 14-activity project and solved to optimality with results showing the intertwined effects of time, cost and quality.

Khang and Myint (1999) apply the model developed by Babu and Suresh (1996) to an actual construction project of a pre-heater tower of a cement factory with 52 activities that is accelerated using overtime only. Duration, cost and quality in the normal and crash modes are estimated by experts. They also adopt the assumption of cost and quality as affine functions of the duration and consider the mean (arithmetic and geometric) of activities quality to define the project quality. Results show that for each given quality level, there exists a budget threshold beyond which it would be extremely expensive to accelerate further. Besides, the authors point out the difficulty to assess the quality reduction in the crash mode (maximum use of overtime) and claim that the linearity assumption between quality and time is questionable. As acceleration is performed with overtime for more than a year to complete the project, the linearity assumption between quality and duration may not hold since it has been shown that a decline in marginal quality is observed after proceeding with overtime work due to fatigue and decrease in motivation (Li et al., 2000). Ultimately productivity of overtime hours is reduced as a result of fatigue, low morale, a higher accident rate, and because workers tend to save effort, adjusting for a longer day or week (Hanna and Sullivan, 2004).

#### *5.1.2. Quality as a non linear increasing function of duration*

Contrary to both previous contributions, Zhang et al. (2014) posit that longer processing times do not always lead to a better quality. First, beyond a duration threshold, quality may degrade as is the case for instance in construction for concreting and compaction activities. Second, the last unit of duration decrease is associated with a higher marginal quality loss than the one corresponding to the first unit of duration reduction. This is consistent for overtime as explained previously. The quality of an activity is therefore defined as a quadratic function of its duration and the authors suggest that parameters of this function can be provided by the project engineers. The project quality is measured by the sum of individual activities quality and the project total cost include costs related to the duration of each activity and tardiness costs. The cost of an activity is also assumed to be a quadratic function of its duration to reflect diminishing marginal productivity. The objective is to minimise the weighted sum of deviations between the project cost, duration and quality and their contractual values. A solution approach based on particle swarm optimisation is applied to an example of an office building project with 19 activities.

Tran et al. (2015) adopt the definition of individual quality as proposed by Zhang et al. (2014) as a quadratic function of duration and the project quality is expressed as a mean of individual qualities. But the cost here is a linear decreasing function of duration. The authors consider for each activity several execution modes with an estimated duration in each mode on one hand and quality and cost computed according to their respective functions of duration on the other hand. The resulting DTCQTP is addressed by a multi-objective algorithm based upon Artificial Bee Colony and implemented on an example of a construction project with 60 activities and a maximum of 5 modes per activity. Simulation results show the superiority of this algorithm in terms of compromise solution compared with four multi-objective approaches including NSGAII. The focus is therefore on the development of an efficient multi-objective algorithm rather than on problem modelling.

It should be noted that none of these two papers provide a detailed methodology to estimate in practice the parameters of the quadratic functions.

### *5.2. Quality as a non linear function of duration and cost*

In an attempt to capture reality more closely, Liberatore and Pollack-Johnson (2013) model the quality of an activity as a non linear function of its duration and cost, assuming the following properties: (*i*) if duration is fixed, spending more money increases quality; (*ii*) if cost is fixed, quality increases with duration. For instance, an expensive high skilled worker will provide over a same duration better quality work than a less expensive lower skilled worker. Furthermore, if the high skilled worker costs twice as much as the low skilled worker, the second property means that the low skilled worker will produce a higher quality outcome spending two days on an activity than the high skilled worker for one day on same activity. The authors also assume that to maintain the same level of quality, one has to pay increasingly more money per unit time of duration reduction.

As a bivariate normal distribution in probability reflects these assumptions, the quality of an activity is expressed as a bivariate normal function of its cost and duration, with parameters values of the function that can be determined applying non linear least squares estimation on several observations of duration, cost and quality. The main objective is to maximise the project quality defined as the minimum of individual qualities subject to budget and deadline constraints; the decision variables are the duration and cost for each activity which determine the quality. A goal programming approach is adopted and the corresponding non linear programs are applied to a translation project with 2 parallel activities (2 documents to be translated) and to a software development example with 7 activities. For both examples, the authors describe in detail the methodology to estimate the parameters of the bivariate normal quality functions.

Quite recently, Fu and Zhang (2016) also suggest to model the individual quality as a non linear function of its duration and cost, based upon the assumptions of Liberatore and Pollack-Johnson (2013). The quality function integrates an additional parameter to adjust the surface shape and when this parameter is zero, the function is the same as Liberatore and Pollack-Johnson (2013). This function expresses that (*i*) quality of an activity is increasing with its duration and cost; (*ii*) for a given level of quality, the relationship between cost and duration is decreasing and convex since more money must be spent for each unit time reduction. Parameters of the function can also be determined using non linear least squares estimation on several observations.

In addition, the authors introduce the meaningful concept of cumulative quality since quality of an activity not only depends on its own quality but also on the quality of its predecessors. To illustrate, consider 3 activities in a construction project where activity 1 is precast pile, activity 2 is precast roof truss and activity 3 is lifting, with activities 1 and 2 as predecessors. As activities 1 and 2 can be processed in parallel, their joint quality can be computed as the mean of their individual qualities. Quality of activity 3 not only depends on its own quality but also on the joint quality of activities 1 and 2 as low qualities of precast pile and precast roof truss with good lifting would not improve the project quality. The quality of this group of 3 activities is the quality of activity 3 multiplied by the average quality of activities 1 and 2 following a computation similar to conditional probability. In such a group, activities are therefore not only bonded by precedence relationships but also by a coordinative relationship. Thus, the activities of a project can be partitioned in several groups of dependent activities with an overall quality computed as described in the above example. If the cumulative quality of a group is lower than a given threshold, rework is required. The objective is to select execution modes for activities so as to minimise rework costs and direct costs that decrease linearly with duration, subject to precedence constraints and resource availabilities. This non linear program is solved using a metaheuristic approach: a Shuffled Frog Leaping Algorithm which is based on Particle Swarm Optimisation and Genetic Algorithms. The approach is applied to an example of a framed railway overpass construction project with 14 activities.

Practical implementation of these approaches requires to collect enough observations of quality, duration and cost for each activity to obtain sharp parameters estimates of the quality function. Furthermore same quality function is assumed for all activities but may not be suitable for all of them, and incidentally Fu and Zhang (2016) report that for a pit excavation activity the data fitting was “relatively acceptable.” This contribution has however the merit of considering dependency relationships between activities quality and to define an overall quality level for a group of quality dependent activities below which rework is needed.

## 6. Quality as an estimated parameter in each execution mode

All the contributions but one that we present in this Section tackle the Discrete Time Cost Quality Trade-off Problem. The quality of an activity is always assumed to be an estimated parameter in each execution mode. In Section 6.1 models are applied to randomly generated instances so that no methodology to estimate the quality is developed. By contrast, Section 6.2 groups the references dealing with real construction projects where the quality of an activity is expressed as a weighted sum of objectively measurable quality indicators in each of its execution modes.

### *6.1. Models with randomly generated instances*

Tareghian and Taheri (2006) add the quality factor in a Discrete Time Cost Trade-off Problem to get the Discrete Time Cost Quality Trade-off Problem (DTCQTP). Each activity can be executed in a single mode amongst several possible modes and to each mode correspond a duration, a cost and a quality that are assumed to be estimated by experts, where the cost decreases with duration and quality increases with duration. The problem is formulated as a standard DTCTP with the additional objective of quality maximisation where the decision variables are binary variables indicating for each activity its execution mode. As in Babu and Suresh (1996) the project quality is the mean of individual qualities and the epsilon constraint method is also adopted. The binary linear programs are applied to 45-activity randomly generated projects using DAGEN, a problem generator developed by Agrawal et al. (1996), and solved to optimality. Simulation results show that with higher budgets, shorter deadlines can be reached at all project quality levels. Higher project quality levels and shorter project durations can also be obtained with higher budgets. Similar results are obtained when the project quality is defined as the geometric mean of individual qualities for they are not very dispersed. Later on, the same authors (Tareghian and Taheri, 2007) utilise the geometric mean only for quality aggregation leading to non linear programs and develop an electromagnetic scatter search heuristic solution approach to solve randomly generated problems up to 20000 activities with a maximum of 15 processing modes per activity.

Recently, Mohammadipour and Sadjadi (2016) also consider the DTCQTP where each execution mode for any activity corresponds to a given duration reduction. Decision variables are binary variables taking a value of one if the duration of an activity is decreased by a given number of periods and zero otherwise. Duration reduction implies a cost increase and a quality decrease that are estimated by experts. But time reduction can also lead to a more global risk impacting on different project objectives like cost, duration, quality and project scopes. The authors therefore consider three objectives to minimise: the total extra cost, the total risk enhancement and the total quality reduction. The problem is formulated as a mixed integer linear program and a Goal attainment approach is used to solve 50 randomly generated instances based on a an example of a two-story building construction project with 18 activities.

To the best of our knowledge, Afruzi et al. (2014) are the only authors who introduce the quality factor in a Multi Resources Constrained Project Scheduling Problem

(MRCPSP) where processing modes can be dependent: if one activity is executed in a specific mode, the activity successor must be processed in a compatible mode, thus reducing the set of possible modes for this activity. Besides, for each mode, an activity can be executed in a crash way (maximum allocation of resources) or in a normal way. For each activity, to the normal way in each mode correspond a normal (maximum) duration, a maximum quality and a vector of renewable resources consumption to which costs are respectively associated. Equivalent definitions hold for the crashing way with a minimum duration, a minimum quality and a larger resources consumption. These parameters are estimated in each mode and in each processing way (crash or not). The project quality is a weighted sum of individual qualities with weights that must also be estimated. The problem is to select modes and processing ways so as to obtain solutions with a good compromise between project duration, cost and quality. A Multi-Objective Imperialist Competitive Algorithm (MOICA) is used to solve the problem, where each solution is coded by three vectors describing respectively: the order in which activities are processed; the selected modes and the selected ways. In each empire, initial colonies are merged with populations obtained by application of several operators on these initial colonies and non dominated solutions are moved to an archive. The best colonies are selected whereas the others are deleted. The algorithm is applied to 25 instances from PSPLIB, a library of projects developed by Kolisch and Sprecher (1997) with 13 to 31 activities and 2 to 4 resources. The performance of MOICA is compared with four other multi-objective metaheuristic algorithms and simulation results show the superiority of MOICA over NSGAII but requires a larger computational time.

### *6.2. Exploiting a database of quality indicators for quality estimation in each mode*

In the following references, more efforts are made to provide an estimation of the quality of an activity in each of its execution modes, exploiting a database of measurable quality indicators but related to highway construction only. The methodology could however be implemented on any project for which there would exist a freely accessible database of quality indicators, which most likely applies to public projects executed many times in the past. In all these contributions, the quality of an activity in each execution mode is expressed as a weighted sum of quality indicator values without specifying how the weights were set.

El-Rayes and Kandil (2005) consider the DTCQTP for a highway construction where each activity can be processed in several modes corresponding to specific combinations of several resources such as material, crew and overtime. Again, we have the following properties. If duration is fixed, spending more money increases quality by the use of higher quality components or more sophisticated machines for example. If cost is fixed, quality increases with duration. For instance two modes may have same cost if mode 1 uses low quality components and overtime and mode 2 uses high quality components and no overtime, then quality and duration in mode 1 are lower than their values in mode 2.

To each mode is associated the cost of the corresponding resources and a duration. For each activity there is a list of several quality indicators and each indicator takes a specific value when the activity is processed in a given mode. For instance, the concrete pavement activity can be processed using a more or less powerful paving machine and different concrete materials leading to several modes in which quality indicators such as air content or thickness of the pavement take different values. Each quality indicator has a weight to reflect its contribution to the quality of the activity but the authors do not explain how the weights were set. The project overall quality is expressed as a weighted sum of individual qualities but again no information is provided on the way these weights were determined. The authors adopt a multi-objective optimisation approach using a Non Sorted Genetic Algorithm (NSGAII) to solve a highway construction project with 18 activities and up to 5 modes per activity.

Mungle et al. (2013) also consider a highway construction project where processing modes for activities correspond to subcontracting options. Like El-Rayes and Kandil (2005) they exploit a database of quality indicators, durations and costs for identical construction projects. An analytic hierarchy process (AHP) technique is used to assess the quality of subcontractors for each activity in the project: quality indicators are ranked and a weight is assigned to them in each mode so as to obtain the quality of an activity for each subcontractor (mode). The project quality is defined as a weighted sum of the minimum individual quality and the average of all individual qualities where a high weight on the minimum ensures that no individual activity has a too low quality level whereas a lower weight implies that the focus is more on the overall average of individual qualities. The project cost is the sum of direct and indirect costs of subcontracting, tardiness penalty cost minus earliness bonus. The problem is to select modes (subcontractors) for activities so as to get the Pareto-optimal set where each Pareto-optimal solution represents a compromise between project duration, cost and quality. The authors point out that the Pareto set of solutions can be large and thus difficult to analyse and comprehend. They thus propose a Fuzzy Clustering Genetic Algorithm approach to reduce the Pareto set to a desirable size. An elitist strategy is used to reduce the archived list of the best non dominated solutions by clustering this list. Instead of selecting the centroid in each cluster, the authors use a fuzzy membership function to determine the cluster centre. A simulation study based upon the same 18-activity highway construction project shows the ability of their approach to generate a better Pareto front than existing approaches such that Multi-Objective Genetic Algorithm and Multi-Objective Particle Swarm Optimisation.

Monghasemi et al. (2015) note that the approach developed by Mungle et al. (2013) although helpful to reduce the Pareto set can not impart multiple criteria. They suggest that a Multi Criteria Decision-Making (MCDM) approach should be implemented to select the best non dominated solution according to decision makers' preferences. They combine a NSGAII with a Shannon entropy technique to assign weights for each sub-objective (project duration, cost and quality) and they apply the methodology to the same highway construction project with 18 activities.

Afshar et al. (2007) deal with the DTCQTP using same definitions of individual qualities and project quality as the ones proposed by El-Rayes and Kandil (2005). They develop a Multi-Objective Ant Colony Optimisation where there is one colony per objective, considering first the objective of minimising the project duration, then cost minimisation and lastly, quality maximisation. Thus, ants of the first colony seek to find solutions that minimise the project duration. These solutions are transferred to the second colony where they are assessed in terms of cost and the pheromone global trail is updated accordingly. New solutions based upon this pheromone trail are transferred to the third colony; their quality is computed and the pheromone trail is again updated. This iterative process of successive solutions transfers continues until a limited number of iterations called a cycle is reached. At the end of each cycle, solutions in the third colony are also assessed in terms of duration and cost and non dominated solutions are recorded in an archive. The pheromone rate is set to its initial value at the beginning of each cycle and the algorithm stops after a predetermined number of cycles. Surprisingly, the approach is not applied to the 18-activity highway construction project but to an example with a very limited number of activities (7 only). Furthermore, no performance comparison is made with existing solution approaches such as the NSGAII proposed by El-Rayes and Kandil (2005).

## 7. Summary and conclusions

Based upon the previous literature review, we draw the following summary and conclusions.

- *Resources.* The vast majority of Time Cost Quality Trade-off Problems studied here consider a single non renewable resource in a continuous framework (CTCTP and Quality) or in a discrete one (DTCTP and Quality). One paper deals with RCSP and rework where quality is not explicitly taken into account (Icmeli-Tukel and Rom, 1997) and two contributions tackle MRCPSP where quality is explicitly considered with possible rework (Fu and Zhang, 2016) and without rework (Afruzi et al. 2014). Quality factor is never introduced in DTRTP or MDTRTP so the quality is never modelled as a function of resources.

- *Activity quality.* When not estimated in each execution mode, activity quality is assumed to be a continuous function of duration only or duration and cost. Quality is a linear increasing function of duration in Babu and Suresh (1996) and Khang and Myint (1999). Quality is a quadratic function of duration in Zhang et al. (2014) and Tran et al. (2015). Quality is expressed as a non linear function of duration and cost in Liberatore and Pollack-Johnson (2013) and in Fu and Zhang (2016). Let us note that quality of an activity has never been formulated directly as a function of resources such as manpower. Rather, quality depends on cost which depends itself on resources. However it has been shown that quality degrades when additional manpower is used for acceleration due to overmanning and overtime (see Li et al., 2000). It would therefore be possible to formulate such a direct relationship between quality and manpower to model a DTRTP with quality.

- *Project quality.* In most papers, project quality is expressed as an arithmetic mean of individual qualities or a geometric mean when individual qualities are dispersed. Such an aggregation has a major flaw: project quality can reach a desired level with individual qualities below acceptable levels. To cope with this aggregation problem, project quality can be expressed as a combination of the minimum and average of individual qualities (Mungle et al., 2013) or only as the minimum of activities quality (Babu and Suresh, 1996 and Liberatore and Pollack-Johnson, 2013). But project quality expressed as the minimum of activities quality is quite questionable since activities differ in their contribution to the project quality. Considering for example a construction project, the foundation is crucial to stability of the building so taking the quality of plastering if minimum as a measure of project quality would make no sense. More relevant is the contribution of Fu and Zhang (2016) that is the only one to impose a minimum level to cumulated quality of subsets of dependent activities so as to avoid rework.

- *Solution approaches.* Multi-objective algorithms are less employed than single-objective formulations. These multi-objective approaches all seek for Pareto optimal solutions, with two major difficulties: the obtained Pareto set may not be well distributed and may be very large which raises the question of how to choose a specific solution. Surprisingly, a lexicographic approach has never been implemented although it is recognised that minimising project duration is the most important goal for managers, then come cost considerations and finally quality improvements (see for instance Khang and Myint, 1999 or Mungle et al., 2013).
- *Project instances.* Amongst all papers, only six different real case based projects are considered, two of them with a very limited number of activities (2 activities for a translation project and 7 activities for a software project), one course development project with 14 activities, two projects with 18 activities (highway construction and robot type palletisation system) and only one large project with 52 activities (pre-heater tower of a cement factory).

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Highlights

- The paper surveys Time Cost Quality Trade-off Problems in a deterministic environment
- The emphasis is on the definition of project activities quality
- We propose a typology based on three main assessment of the quality of an activity
- We report the absence of a direct relationship between quality and resources
- Lexicographic optimisation has never been used