Innovative Applications of O.R.

Optimizing temporary work and overtime in the Time Cost Quality Trade-off Problem

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ABSTRACT

In spite of its significant contribution to project success, quality has been scarcely addressed in the literature on deterministic project scheduling problems. Although it is recognized that higher qualities are associated with longer processing times, no relationship between quality and resource consumption has been analytically derived to support this statement. As manufacturing projects can be accelerated using additional manpower such as overtime and temporary workers, we derive an analytical relationship between quality and manpower since overtime and overmanning negate quality. We also take into account productivity losses due to overmanning. Contrary to most previous contributions that focus on the project overall quality as an aggregation of quality levels attained at the individual activities, we impose each activity to reach a minimum quality threshold, which is consistent with project management practices. Consequently, we develop a mixed integer linear programming (MILP) to optimize temporary work and overtime so as to accelerate a project with quality and productivity considerations. The objective is to simultaneously determine for each activity the number of permanent, temporary and overtime workers over the processing periods in order to minimize the makespan, the total cost and the overall quality losses subject to individual quality constraints, precedence relationships, nonpreemption and availability of resources. Our approach is successfully applied on numerous instances based on a real project of a high speed locomotive as well as on other projects taken from the literature.

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1. Introduction

The Time Cost Trade-off Problem (TCTP) has been widely studied in the literature on deterministic project scheduling problems (for a survey, see Weglarz, Jozefowska, Mika, & Waligora, 2011 or Hartmann & Briskorn, 2010). However, projects that are delivered on time within budget can hardly be considered as successful if the quality of the deliverable is poor. The reason is that quality products make an important contribution to long-term revenue and profitability and enable companies to maintain their reputation and customer loyalty. It is thus surprising that only a few references address the quality issue in the TCTP in spite of its significance (for a survey, see Orm & Jeunet, 2018).

A project schedule often needs to be shortened to fit within contractually time. This almost always requires additional manpower, namely overtime and temporary work, since the majority of manufacturing systems are not fully automatized. As a result,

cost increases and quality declines. Overtime implies fatigue that affects product quality (Babu & Suresh, 1996; Beckers et al., 2004; Hanna & Sullivan, 2004; Khang & Myint, 1999; Li, Love, & Drew, 2000; Mahmud, 2015). Temporary workers favor overmanning which also negates quality (Hanna, Chang, Lackney, & Sullivan, 2007; Li et al., 2000). Besides, it is notorious that overtime leads to productivity losses (Broschak & Davis-Blake, 2006; Gunduz, 2004; Hanna & Sullivan, 2004; Kaming, Holt, Kometa, & Olomolaiye, 1998). Furthermore, overmanning also has a negative impact on productivity (Gibson, 2015; Gunduz, 2004; Gunduz & Hanna, 2005; Hitchens, Wagner, & Birnie, 1992; Kaming et al., 1998). Considering the adverse effects of additional manpower on quality and on productivity, the question arises how to plan manpower requirements so as to accelerate a manufacturing project at the lowest possible cost while meeting quality constraints on activities?

To address this research question, we develop a tactical manpower planning model with the objectives of minimizing the makespan, the total cost of manpower and overall quality losses of a manufacturing project, subject to manpower requirements, precedence and nonpreemption constraints, human resource availability and minimum quality levels for activities. We therefore

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deal with the Time Cost Quality Trade-off problem where the resources are limited to three types of manpower: permanent workers, overtime, and temporary workers since in the mid-run, tools and equipment remain unchanged. We assume that each activity requires a single specific skill, like welding or cabling and each worker is endowed with a single skill. This is consistent for most manufacturing projects contrary to services projects. A worker can process only one activity at a time but several workers with the same skill can simultaneously process one activity. The completion of any activity requires a work content expressed in man-days that must be met by a proper allocation of workers over the processing periods, namely the work profile (Fundeling & Trautmann, 2010). Since the additional manpower is inherently flexible, the work profile is assumed to be flexible, meaning that the number of workers allocated to an activity can vary from one processing period to the next. For instance, a work content of 12 man-days for a given activity with a constant profile of 2 men for 6 days (normal duration) can be completed in 4 days with a flexible profile of 4 men for 2 days and 2 men for 2 days. In the latter case, there is overmanning for 2 days which may result in productivity losses. We therefore provide a new formulation of the work content constraint to account for productivity losses. When accelerated, an activity experiences a quality decline due to the additional manpower. We analytically derive the impact of overtime and temporary work on quality that we incorporate into the constraints of minimum quality levels. The planning problem is formulated as a Mixed Integer Linear Program for optimizing the allocation of permanent and temporary workers as well as overtime hours to each processing period of every activities.

Examining the Time Cost Quality trade-off in a project management setting appears to be an understudied area in the Operations Management literature relative to its importance in practice. Quality refers to the degree to which products fulfill a number of requirements that have been deemed necessary. In most contributions, quality is measured by an indicator between zero and one reflecting the percentage of validated items in quality control inspection lists to verify compliance with the applicable contract requirements (Orm & Jeunet, 2018). Tareghian and Taheri (2006) incorporate such a quality indicator into a Discrete Time Cost Trade-off Problem (DTCTP) with a single non-renewable resource where each activity can be completed in several execution modes. Each mode is assigned with an estimated cost, duration and quality. The objective is to find modes for activities so as to minimize the makespan or to minimize the cost or to maximize the overall quality expressed as the mean of individual qualities. Thus, they develop three integer programming models where each model optimizes one of the given objectives under desired bounds constraints on the other two (epsilon constraint method). Afruzi, Najafi, Roghanian, and Mazinani (2014) extend this approach to a multiple resources setting where each activity can be executed either in a normal mode (minimum allocation of resources) or in a crashed mode (maximum allocation of resources) with dependent mode-activity assignments: the choice of a mode for a given activity implies that successor activities are completed in the same mode. The authors develop a Multi-Objective Imperialist Competitive Algorithm to find the best compromises between time, cost and quality of the project under resources and mode identity constraints. The project overall quality is expressed as a weighted sum of individual qualities. In order to be applicable to real case problems, both previous approaches thus imply an estimation of duration, cost and quality for each activity in their numerous execution modes. Only Babu and Suresh (1996) formulate the quality of an activity as a linear function of duration and since duration is also assumed to decrease linearly with a single non-renewable resource, thus quality is a linear increasing function of this single resource (cost). Consequently the authors implicitly assumed that

increasing the resources has no impact on productivity. Like in Tareghian and Taheri (2006), three linear programming models are developed to optimize one of these entities by assigning desired bounds on the other two, with decision variables consisting of activity completion times. Again, the overall project quality results from an aggregation of quality levels attained at the individual activities.

The quality criterion has never been integrated into the Multiple Discrete Time Resources Trade-off Problem (MDTRTP) which itself remains understudied in the literature. Naber and Kolisch (2014) address the Resource-Constrained Project Scheduling Problem with flexible resource profiles (FRCPS), where the objective is to determine start times and resource profiles for all activities so as to minimize the makespan, subject to precedence relationships and resource constraints.

Besides, optimization of temporary work and overtime has received little attention in the literature on project scheduling. Yang, Guenes, and Brien (2004) tackle the single resource TCTP where jobs can be processed in regular and overtime modes. The objective is to minimize the total cost of overtime and tardiness under precedence and nonpreemption constraints. Heimerl and Kolisch (2010) consider not only overtime but also temporary work for simultaneously scheduling independent projects requiring multi-skilled human resources with the objective of minimizing labor costs. Thus, each worker masters several skills, and workers may perform differently with respect to a same skill (heterogeneous efficiencies) with no learning or forgetting effect (static efficiencies).

To the best of our knowledge, our paper is the first to integrate quality into an optimization model for additional manpower allocation to accelerate a manufacturing project. We consider not only overtime but also temporary work and their impact on quality and on productivity. In this regard, we provide a thorough analysis of these impacts as well as their mathematical formulation. None of the existing contributions formulates the quality of an activity as a function of several renewable resources whereas we provide a mechanism for modeling this relationship. Thus, with very few parameters to estimate for each activity, we can obtain the cost, the quality and the duration associated with an almost infinite number of execution modes. This makes the implementation of our approach in practice much easier than multi-mode modeling approaches that require an estimation of parameters in each activity execution mode. Besides, existing contributions focus on the maximization of the overall quality of a project defined as an aggregation of individual qualities. But such an aggregation has an inherent flaw: the project quality can be acceptable with some unacceptable individual qualities as long as they are offset by other high individual qualities (see Babu & Suresh, 1996 or Khang & Myint, 1999). In practice however, the quality of each activity must reach a minimum level which may be estimated by the rate of unacceptable flaws in the checklist. We thus include in our model minimum quality constraints on each activity.

Contrary to existing papers that adopt either an epsilon constraint method or a multi-objective approach, we use a lexicographic optimization method where the makespan is to be minimized first, then the total cost and ultimately the overall quality losses while meeting individual quality constraints. This preference order of the objectives is consistent with managers goals (Mungle, Benyoucef, Son, & Tiwari, 2013). The model is successfully applied to a case study based on a real manufacturing project of a very high speed train motor coach at Alstom, the French company operating worldwide in rail transport markets. In addition, several realistic instances from the extant literature were also used to validate the performance of our model.

The paper is organized as follows. Section 2 describes our planning problem and gives insights about the effects of additional manpower on processing times and on quality. In Section 3,

these effects are discussed in detail and analytically derived to achieve the formulation of our planning problem. Section 4 is dedicated to the numerical results. Finally, Section 5 summarizes our contribution and outlines directions for future work.

2. Problem description

In this Section, we state the planning problem and we briefly depict the impacts of additional manpower.

We consider a project represented as an Activity-on-Arrow graph with a set of activities $V = \{0, 1, \dots, n, n+1\}$ where 0 and $n+1$ are dummy activities denoting respectively the start and finish of the project. Arcs represent precedence relationships between activities; each activity j having a set $\Gamma^{-1}(j)$ of predecessor activities and a set $\Gamma(j)$ of successors. Each activity requires a single skill k , with $k = 1, \dots, K$ where K is the total number of different skills needed to complete the project and $K \leq n$. Workers are each endowed with a single skill and $\mathcal{P}_k$ denotes the number of workers with skill k allocated to the project. We let V_k be the subset of activities requiring skill k . When the project is not accelerated or said to be executed in a normal mode, its makespan $C_{\max}^{\text{nor}}$ is obtained by allocating to each activity j a number P_j^{nor} of workers with skill k in each period of its normal processing time d_j^{nor} . The work content in man-days of activity j is thus equal to $P_j^{\text{nor}} \cdot d_j^{\text{nor}}$. For dummy activities, we have $d_0^{\text{nor}} = d_{n+1}^{\text{nor}} = 0$.

A lower bound $\underline{C}_{\max}$ on the makespan can be derived from lower bounds $\{\underline{d}_j\}_{j=1,\dots,n}$ on activities durations obtained by allocating to each activity the maximum number of workers and overtime hours in each processing period. We let ES_j be the earliest start time of activity j based on lower bounds $\{\underline{d}_j\}_{j=1,\dots,n}$ and LF_j , its latest finish time derived from upper bounds $\{\overline{d}_j\}_{j=1,\dots,n}$. We define $\mathcal{T}_j = \{ES_j, \dots, LF_j\}$ as the set of feasible processing periods of activity j .

The objective is to sequentially minimize the project makespan, the total cost and the overall quality losses by optimizing the permanent and temporary workforce and overtime subject to work content satisfaction for each activity, precedence relationships, nonpreemption, resource availability and individual qualities above acceptable thresholds. Decision variables p_{jt} , u_{jt} and h_{jt} denote respectively the number of permanent workers, temporary workers and overtime hours assigned to the execution of activity j in period t . Additionally, z_{jt} is a binary variable that takes a value of 1 if activity j is being processed in period t and 0 otherwise. Thus, after optimization, the duration d_j of an activity j is $d_j = \sum_{t \in \mathcal{T}_j} z_{jt}$. The notations and definitions are summarized in Table 5 in Appendix A.

Fig. 1 provides a brief description of the planning problem on the left hand side, and gives an overview of the impacts of additional manpower on the duration and on the quality on the right hand side. Each of these impacts is studied in detail in Section 3 as indicated in Fig. 1. The influence of additional manpower on the duration is examined in Section 3.1, which corresponds to the blue arrows (solid line) in the figure. Temporary work favors overmanning and hence productivity losses that modify the formulation of the work profile, as detailed in Section 3.1.1. Overtime also leads to productivity losses beyond a threshold of hours as discussed in Section 3.1.2. We finally obtain a formulation of the work profile that, together with the work content, allow for deriving the relationship between manpower usage and duration (Section 3.1.3).

Next, the effects of additional manpower on quality are analyzed in Section 3.2 with individual impacts represented by the red arrows (dotted line) in Fig. 1. Temporary work negates quality through overmanning (Section 3.2.1). The negative impact of overtime on quality is mainly due to a decreased attention to quality standards and expectations at the end of the working day (Section 3.2.2). Since quality is formulated as a function of

manpower and as manpower usage defines the processing time, we derive the relationship between quality and duration in Section 3.2.3.

3. Analysis of the impacts of additional manpower and formulation

In this Section, we first provide a formulation of the relationship between additional manpower and processing time (Section 3.1), by analyzing the impact of overmanning and overtime on productivity. Second, we derive the relationship between quality and additional manpower (Section 3.2.3), distinguishing again the effect of overmanning and overtime on quality. These relationships are finally incorporated into the formulation of the optimization program that we give in Section 3.3.

3.1. Relationship between additional manpower and processing time

Previous contributions assume a linear relationship between the processing time and the cost. Since the cost is proportional to the hours worked, this amounts to assume constant returns to scale (Babu & Suresh, 1996 and Khang & Myint, 1999). However, as documented in our introduction, several studies advocate that additional manpower causes productivity losses which result in decreasing returns to scale. The relationship between the processing time and the additional manpower is therefore convex as will be illustrated at the end of this Section. In order to analytically incorporate potential productivity losses in our model, the work content constraints need to be reformulated. These constraints state that the number of workers allocated to an activity over its processing periods must satisfy its work content, which is written as

$$\sum_{t \in \mathcal{T}_j} (W_{jt}^R + W_{jt}^O) = P_j^{\text{nor}} \cdot d_j^{\text{nor}} \quad \forall j = 1, \dots, n, \quad (1)$$

where W_{jt}^R and W_{jt}^O designate the number of productive workers during regular and overtime hours in period t respectively. We have $W_{jt}^R \equiv W_j^R(p_{jt} + u_{jt})$ and $W_{jt}^O \equiv W_j^O(h_{jt})$ and the shapes of these functions are discussed in the next Subsections.

3.1.1. Impact of overmanning on productivity

Overmanning for activity j in period t is defined as the situation where the number of workers on this activity in regular working time exceeds the normal number P_j^{nor} in that period, that is $p_{jt} + u_{jt} > P_j^{\text{nor}}$. Besides, capacity constraints on workstations limit overmanning to a maximum number of P_j^{max} workers (with skill k) in each period. Beyond P_j^{nor} , the workforce can include not only temporary workers but also permanent workers since some of them become available in some periods, as a result of acceleration. Thus we can have $p_{jt} + u_{jt} > P_j^{\text{nor}}$ with $p_{jt} > P_j^{\text{nor}}$.

We assume that workers with a same skill have a same productivity, be these workers permanent or temporary. First, most of the empirical literature finds that temporary workers are not less committed than permanent workers (for a survey, see Cuyper et al., 2008). Second, for the skilled work we consider here, a quite short training period is sufficient to guarantee a same productivity. Third, companies hire the same temporary workers as often as possible. Consequently, productivity is only affected by overmanning and not by heterogeneous skill levels among workers (permanent or temporary). Overmanning implies productivity losses due to limited workspace (site congestion), crew interference and dilution of supervision (Gunduz, 2004; Gunduz, 2004; Kaming et al., 1998) or because the presence of temporary workers may create conflict and tension in work groups (Broschak & Davis-Blake, 2006). In their literature review, Hanna et al. (2007) concluded that all prior studies demonstrate a negative effect of overmanning on

Fig. 1. The impact of additional manpower on quality and on processing times.

productivity with a variance in results which can be explained by the heterogeneity of projects and work types, site conditions, and definitions of overmanning. However, no shape of the relationship between productivity and overmanning was provided. To the best of our knowledge only Gunduz (2004) reported quantitative relationships from several past studies. These relationships can pessimistically be approximated by a linear function. Letting η_{jt} be the variation rate of productivity, we have

$$W_{jt}^R = (1 - \eta_{jt}) \cdot (p_{jt} + u_{jt}) \quad \forall p_{jt} + u_{jt} > P_j^{\text{nor}}, \quad (2)$$

where W_{jt}^R is the number of workers in period t who actually contribute to the execution of activity j . The linearity assumption between the productivity variation rate, η_{jt} , and the overmanning rate, $((p_{jt} + u_{jt})/P_j^{\text{nor}}) - 1$, is written as

$$\eta_{jt} = \gamma_j \cdot \left(\frac{p_{jt} + u_{jt}}{P_j^{\text{nor}}} - 1 \right), \quad (3)$$

where coefficient $\gamma_j > 0$ measures the impact of overmanning on productivity losses. Replacing in Eq. (2) the rate η_{jt} with its expression in Eq. (3), we obtain

$$W_{jt}^R \equiv W_j^R(p_{jt} + u_{jt}) = \begin{cases} p_{jt} + u_{jt}, & \forall p_{jt} + u_{jt} = 0, \dots, P_j^{\text{nor}} \\ (1 + \gamma_j) \cdot (p_{jt} + u_{jt}) - (\gamma_j/P_j^{\text{nor}}) \cdot (p_{jt} + u_{jt})^2, & \forall p_{jt} + u_{jt} = P_j^{\text{nor}} + 1, \dots, P_j^{\text{max}}. \end{cases} \quad (4)$$

Fig. 2 plots function $W_j^R(p_{jt} + u_{jt})$ for several values of γ_j and $P_j^{\text{nor}} = 3$. When $\gamma_j = 0$, overmanning has no impact on productivity. We have $W_j^R(p_{jt} + u_{jt}) = p_{jt} + u_{jt}$ which corresponds to a linear relationship between manpower and duration (doubling the workforce reduces by half the processing time).

When $\gamma_j > 0$, we have a diminishing marginal productivity and function $W_j^R(p_{jt} + u_{jt})$ reaches its maximum value for $p_{jt} + u_{jt} = (1 + \gamma_j)P_j^{\text{nor}}/2\gamma_j$. This implies that beyond a number $\lfloor (1 + \gamma_j)P_j^{\text{nor}}/2\gamma_j \rfloor$ of workers, adding a worker does not help to reduce the processing time. For instance, with $\gamma_j = 0.50$, function $W_j^R(p_{jt} + u_{jt})$ reaches its maximum for $\lfloor (1 + \gamma_j)P_j^{\text{nor}}/2\gamma_j \rfloor = 4$

Fig. 2. Graph of function W_j^R for several values of γ_j and $P_j^{\text{nor}} = 3$.

workers. We have $W_j^R(4) = W_j^R(5) = 3.33$ meaning that 4 or 5 workers both provide the equivalent work of 3.33 workers who would actually make the activity progressing (see curve for $\gamma_j = 0.50$ in Fig. 2).

Finally, there exists a value of γ_j above which acceleration is precluded because the impact of overmanning on productivity is too strong. This value of γ_j is obtained by solving $W_j^R(P_j^{\text{nor}} + 1) \leq P_j^{\text{nor}}$ using Eq. (4), which gives $\gamma_j \geq P_j^{\text{nor}}/(P_j^{\text{nor}} + 1)$ and for which we would set $P_j^{\text{max}} = P_j^{\text{nor}}$. In our example, no acceleration is possible for $\gamma_j \geq 3/4$.

To linearize function $W_j^R(p_{jt} + u_{jt})$ given in Eq. (4) with possible values for $p_{jt} + u_{jt}$ in the set $\{0, \dots, p_j^{\max}\}$, we note y_{jtl} the binary variable that takes a value of 1 if $p_{jt} + u_{jt}$ takes a value of l with $l \in \{0, \dots, p_j^{\max}\}$ and 0 otherwise. Variables $p_{jt} + u_{jt}$ can therefore be written as

$$p_{jt} + u_{jt} = \sum_{l=0}^{p_j^{\max}} l \cdot y_{jtl} \quad \forall j = 1, \dots, n, \quad t \in \mathcal{T}_j, \quad (5)$$

with the following constraints that guarantee that the number of workers $p_{jt} + u_{jt}$ can take one and only one value

$$\sum_{l=0}^{p_j^{\max}} y_{jtl} = 1 \quad \forall j = 1, \dots, n, \quad t \in \mathcal{T}_j. \quad (6)$$

We therefore linearize function $W_{jt}^R \equiv W_j^R(p_{jt} + u_{jt})$ as follows:

$$W_{jt}^R = \sum_{l=0}^{p_j^{\max}} W_j^R(l) \cdot y_{jtl} \quad \forall j = 1, \dots, n, \quad t \in \mathcal{T}_j, \quad (7)$$

where values of $W_j^R(l)$ are simply computed beforehand using Eq. (4).

3.1.2. Effects of overtime on productivity

Overtime is most commonly defined as the work performed over 8 hours a day and 40 hours a week (e.g. Hanna, Taylor, & Sullivan, 2005). It has been well documented in the literature that overtime can adversely affect labor productivity due to fatigue, low morale and a phenomenon described by the U.S. Army where workers tend to pace themselves for longer days (U.S. Army Corps of Engineers, 1979). Rojas (2008) posits that 4 to 5 continuous weeks of overtime with 50 hours a week lead to a loss of labor efficiency of about 15% and can easily exceed 40% after 10 to 12 weeks. This finding is consistent with several studies of overtime on labour efficiency in various sectors and published by organizations such as the National Electrical Contractors Association (NECA) (1989), (Mechanical Contractors Association of America (MCAA) (2011), the Business Roundtable (BRT) (1980), or the Construction Industry Institute (Thomas & Raynar, 1997). Alvanchi, Lee, and Abourizk (2012) also stress out that productivity losses may increase non-linearly with weeks of overtime because complete relief may not be achieved during the weekend.

Other studies advocate that overtime has no negative impact on productivity in specific contexts. Pencavel (2014) showed that below 49 weekly hours, variations in output are proportional to variations in hours, applying the least squares method to 122 weekly observations on munition workers. Circadian, a research and consulting company, stated that below 10 hours of overtime per week, the productivity is not affected for activities of maintenance and construction (Circadian, 2016). Beckers et al. (2004) conducted a survey-study among a representative sample of Dutch employees and did not find any association between fatigue and moderate overtime (1 to 8 hours a week). They even observed positive outcomes from overtime under favorable overtime working conditions such as voluntary overtime work, job variety, freedom to decide how to do the job and rewards (premium payment, recognition, promotions). These studies therefore suggest that below 8 to 10 overtime hours a week, productivity is not affected by overtime. As overtime regulation in Europe provides that full-time employees shall work overtime for a maximum of 8 hours a week, applying this regulation leads to getting the same productivity for overtime hours than for regular hours. We thus have

$$W_{jt}^O \equiv W_j^O(h_{jt}) = h_{jt}/H_R \quad \forall j = 1, \dots, n, \quad t \in \mathcal{T}_j. \quad (8)$$

Consequently, in our model, only overmanning has a negative impact on productivity.

Table 1

Additional manpower and processing time.

d_j	Overmanning mainly	Overtime only	
	$(p_{jt} + u_{jt} - p_j^{\text{nor}})_{t=1..d_j}$	$\sum_{t=1}^{d_j} h_{jt}/H_R$	$\sum_{t=1}^{d_j} h_{jt}/H_R$
7	(0,0,0,0,1,1,1)	0.3429	3
6	(1,1,1,1,1,1)	0.6856	6
5	(2,2,2,2,2)	0.4283	9

3.1.3. Processing time as a function of additional manpower and illustration

The constraints on work content satisfaction in Eq. (1) can be rewritten using the expressions of $W_{jt}^R \equiv W_j^R(p_{jt} + u_{jt})$ and $W_{jt}^O \equiv W_j^O(h_{jt})$ in Eq. (4) and Eq. (8), respectively

$$\begin{aligned} & \sum_{\{t \in \mathcal{T}_j | p_{jt} + u_{jt} \leq p_j^{\text{nor}}\}} (p_{jt} + u_{jt}) + \sum_{\{t \in \mathcal{T}_j | p_{jt} + u_{jt} > p_j^{\text{nor}}\}} ((1 + \gamma_j) \cdot (p_{jt} + u_{jt}) \\ & - (\gamma_j/p_j^{\text{nor}}) \cdot (p_{jt} + u_{jt})^2) + \sum_{t \in \mathcal{T}_j} h_{jt}/H_R = p_j^{\text{nor}} \cdot d_j^{\text{nor}}, \\ & \forall j = 1, \dots, n. \end{aligned} \quad (9)$$

With Eq. (9) we can now illustrate the relationship between duration and additional manpower. Let us consider an activity j with $p_j^{\text{nor}} = 3$ and $p_j^{\max} = 5$ workers, $d_j^{\text{nor}} = 8$ days, $H_R = 8$ hours a day and an impact of overmanning on productivity $\gamma_j = 0.0857$. In the normal mode, activity j is processed by 3 workers a day over 8 days so the work content is 24 man-days. Table 1 provides for each reduced duration $d_j = 7, 6, 5$ two types of manpower allocation, one with the highest number of regular workers (overmanning mainly) and one with overtime only.

As shown in Table 1, to get a duration $d_j = 7$ days using mainly workers in regular hours, one possible manpower allocation consists in adding to the three workers, one worker in overmanning per day over the last three days and to use a total of $0.3429 \times 8 = 2.7432$ overtime hours. Following Eq. (4), we have $W_j^R(3+1) = (1 + 0.0857) \times (3+1) - (0.0857/3) \times (3+1)^2 = 3.8857$ which means that 4 workers are equivalent to 3.8857 efficient ones. Following Eq. (9), the work content is satisfied since $4 \times 3 + 3 \times W_j^R(4) + 0.3429 = 12 + 3 \times 3.8857 + 0.3429 = 24$. Obviously, there is a multitude of manpower combinations to get $d_j = 7$ and the optimal one will depend on workers' availabilities and unit costs of manpower. With overtime only (right side of Table 1), a duration $d_j = 7$ days is reached with a total of $3 \times 8 = 24$ hours of overtime since we have $7 \times W_j^R(3) + 3 = 7 \times 3 + 3 = 24$.

Fig. 3 plots the duration d_j as a function of additional manpower $\sum_{t=1}^{d_j} (p_{jt} + u_{jt} - p_j^{\text{nor}}) + \sum_{t=1}^{d_j} h_{jt}/H_R$ for the two types of allocation displayed in Table 1. As previously detailed, a duration $d_j = 7$ days is obtained with the work of 3.3429 additional workers when overmanning is mainly used or with 24 overtime hours which corresponds to the daily work of 3 additional workers. Due to productivity losses when there is overmanning, the relationship between the duration of an activity and manpower is decreasing and convex, as illustrated in Fig. 3 (blue dotted curve, overmanning mainly). This relationship is linear when overtime is exclusively utilized (red solid line in Fig. 3) or if $\gamma_j = 0$.

3.2. Relationship between quality of an activity and additional manpower

Quality of individual activities can be measured as a percentage of the checked items in their quality control checklist. The highest quality level q_j^{nor} which is reached in normal mode usually equals one, meaning that 100% of the items are checked. We let parameter λ_j^R denote the quality loss resulting from one day of regular

Fig. 3. Relationship between duration and manpower.

work (H_R hours) in situation of overmanning and parameter λ_j^O , the quality loss associated with one hour of overtime. For instance a value $\lambda_j^R = 0.025$ means that one worker in situation of overmanning for H_R hours (one day) induces on average the non-validation of 2.50% of the checklist items of activity j . A value $\lambda_j^O = 0.00625$ expresses that one hour of overtime leads on average to the non-validation of 0.625% of the items in the checklist. Parameters λ_j^R and λ_j^O can also be interpreted as probabilities of deficiency occurrence (Kim et al., 2012). Letting $L_{jt}^R \equiv L_j^R(p_{jt} + u_{jt}; \lambda_j^R)$ and $L_{jt}^O \equiv L_j^O(h_{jt}; \lambda_j^O)$ be respectively the quality losses associated with the use of overmanning and overtime on activity j in period t , the individual quality q_j can be written as

$$q_j = q_j^{\text{nor}} - \sum_{t \in \mathcal{T}_j} (L_{jt}^R + L_{jt}^O). \quad (10)$$

While numerous studies have investigated the impact of overtime on quality, the effect of overmanning on quality remains scarcely explored. To the best of our knowledge, Li et al. (2000) are the only authors who quantified the negative impact of both overtime and additional resources on quality. Using data collected from building construction projects, they assessed the effect of different combinations of overtime and additional resources on the quality of these projects. Overtime and additional resources were expressed as percentages but the percentage bases were not reported. Consequently, this study is hardly exploitable to infer a relationship between quality of an activity and additional manpower. Nevertheless, it has at least the merit to show that the impact of overtime hours on quality is about twice the effect of overmanning hours

$$\lambda_j^O = \rho \cdot \lambda_j^R / H_R, \quad \rho \simeq 2. \quad (11)$$

In the remainder of this Section, we discuss the shapes of functions L_j^R and L_j^O to formulate a continuous and direct relationship between quality and manpower, whereas existing contributions focus solely on the relationship between quality and processing time (for a survey, see Orm & Jeunet, 2018).

3.2.1. Quality and overmanning

As previously mentioned, the study of Li et al. (2000) does not allow to derive an analytical relationship between quality and overmanning. We thus relied upon the experience of Alstom's managers. They posit that a linear relationship between quality and overmanning can reasonably be assumed when overmanning is limited to a few additional workers per activity with

dedicated workspaces. The quality decrease is therefore mainly due to a dilution of supervision and not to a site congestion. According to these managers, if workstations were not designed to accommodate extra workers then congestion would lead to quality losses exponentially increasing with overmanning (the relationship between overmanning and quality would be concave). But in most manufacturing industries there exists a buffer capacity for temporary purposes so we can reasonably assume that

$$\begin{aligned} L_{jt}^R &\equiv L_j^R(p_{jt} + u_{jt}) \\ &= \begin{cases} 0, & \forall p_{jt} + u_{jt} = 0, \dots, P_j^{\text{nor}} \\ \lambda_j^R \cdot (p_{jt} + u_{jt} - P_j^{\text{nor}}), & \forall p_{jt} + u_{jt} = P_j^{\text{nor}} + 1, \dots, P_j^{\text{max}}. \end{cases} \end{aligned} \quad (12)$$

To linearize $L_j^R(p_{jt} + u_{jt})$ we adopt a similar approach to the one we used for linearizing $W_j^R(p_{jt} + u_{jt})$ in Eq. (7). We obtain

$$L_{jt}^R = \sum_{l=0}^{P_j^{\text{max}}} L_j^R(l) \cdot y_{jlt} \quad \forall j = 1, \dots, n, \quad t \in \mathcal{T}_j, \quad (13)$$

with the same binary variables as in Eq. (5) and with values of quality losses $L_j^R(l)$ computed beforehand as follows:

$$L_j^R(l) = \begin{cases} 0, & \forall l = 0, \dots, P_j^{\text{nor}} \\ \lambda_j^R \cdot (l - P_j^{\text{nor}}), & \forall l = P_j^{\text{nor}} + 1, \dots, P_j^{\text{max}} \end{cases} \quad \forall j = 1, \dots, n. \quad (14)$$

3.2.2. Quality and overtime

In the literature, quality is assumed to be a function of the processing time which in turn depends on the amount of resources. Zhang, Du, and Zhang (2014) formulate the quality of an activity as a quadratic function of its processing time for specific activities in construction like concreting and compaction. In Liberatore and Pollack-Johnson (2013), the quality of an activity is assumed to be a bivariate normal function of its cost and duration in new product development or when efficiencies of human resources are heterogeneous. Therefore, none of these non-linear relationships can be used to formulate the quality decrease due to acceleration with additional manpower in the manufacturing environment we consider. We thus assume that quality linearly decreases with duration, as in Babu and Suresh (1996) and Khang and Myint (1999) who consider a project expedited with overtime only. This amounts to assuming that quality linearly decreases with overtime, which is a reasonable assumption since the law significantly limits overtime. Furthermore, Alstom's quality managers supported this assumption. This is written as

$$L_{jt}^O = \lambda_j^O \cdot h_{jt}. \quad (15)$$

Proof. When there is no overmanning, activity j uses a number $P_j^{\text{nor}} \cdot d_j$ of regular workers over its processing time d_j . This comes from the usual assumption that the number of permanent workers assigned to any activity in each period is at least equal to this number in the normal mode, $p_{jt} \geq P_j^{\text{nor}}$ (see for instance Naber & Kolisch, 2014). Letting S_j be the actual start time of activity j , the constraint on its work content (Eq. (9)) is written as $P_j^{\text{nor}} \cdot d_j + \sum_{t=S_j, \dots, S_j+d_j} h_{jt} (h_{jt}/H_R) = P_j^{\text{nor}} \cdot d_j^{\text{nor}}$. This gives the volume of overtime hours to reduce the processing time from d_j^{nor} to d_j , that is $\sum_{t=S_j, \dots, S_j+d_j} h_{jt} = H_R \cdot P_j^{\text{nor}} \cdot d_j^{\text{nor}} - H_R \cdot P_j^{\text{nor}} \cdot d_j$. Besides, from Eq. (10), we have $q_j = q_j^{\text{nor}} - \lambda_j^O \cdot \sum_{t=S_j, \dots, S_j+d_j} h_{jt}$.

Table 2
Additional manpower and processing time.

d_j	Overmanning mainly		Overtime only	
	Add. workers	q_j	Add. workers	q_j
7	3.3429	0.9079	3	0.85
6	6.6856	0.8157	6	0.70
5	10.4283	0.7286	9	0.55
4	14.6281	0.6186	12	0.40
3	20.5419	0.4729	15	0.25

Substituting the sum of overtime hours for its expression into that of q_j , we get an affine function between q_j and d_j

$$q_j = (\lambda_j^O \cdot H_R \cdot P_j^{\text{nor}}) d_j + (q_j^{\text{nor}} - \lambda_j^O \cdot H_R \cdot P_j^{\text{nor}} \cdot d_j^{\text{nor}}),$$

$$\forall p_{jt} + u_{jt} = P_j^{\text{nor}}, \quad t = S_j, \dots, S_j + d_j. \quad (16)$$

□

3.2.3. Relationships between quality, additional manpower, and processing time and numerical illustration

Following our assumptions on functions L_j^R and L_j^O , we can provide a new expression for quality q_j , using Eqs. (12) and (15)

$$q_j = q_j^{\text{nor}} - \lambda_j^R \sum_{\{t \in T_j | p_{jt} + u_{jt} > P_j^{\text{nor}}\}} (p_{jt} + u_{jt} - P_j^{\text{nor}}) - \lambda_j^O \sum_{t \in T_j} h_{jt}. \quad (17)$$

Let us now study the relationship between quality and duration. This relationship is linear when only overtime is used, as shown by Eq. (16). When overmanning is combined with overtime, an analytical relationship between the quality q_j and the processing time d_j can hardly be derived for there exists several allocations of additional workers over processing periods leading to a same duration d_j with different impacts on quality. However, under some assumptions, we can first derive a relationship between overmanning and duration and next between quality and duration. With no overtime and if we assume a constant number of workers in overmanning over the d_j processing periods, $p_{jt} + u_{jt} = p_j + u_j$, $\forall t = S_j, \dots, S_j + d_j$, the constraint on the work content is written as $d_j \cdot W_j^R(p_j + u_j) = P_j^{\text{nor}} \cdot d_j^{\text{nor}}$. Replacing $W_j^R(p_j + u_j)$ with its expression (see Eq. (4)), we get $d_j \cdot ((1 + \gamma_j) \cdot (p_j + u_j) - (\gamma_j / P_j^{\text{nor}}) \cdot (p_j + u_j)^2) - P_j^{\text{nor}} \cdot d_j^{\text{nor}} = 0$. This quadratic equation has the following acceptable root which provides a non linear relationship between overmanning and duration

$$p_j + u_j = (P_j^{\text{nor}} / 2\gamma_j) \cdot \left((1 + \gamma_j) - \frac{1}{d_j} \sqrt{(1 + \gamma_j)^2 \cdot d_j^2 - 4\gamma_j d_j^{\text{nor}} \cdot d_j} \right). \quad (18)$$

Besides, Eq. (17) gives $q_j = q_j^{\text{nor}} - \lambda_j^R d_j (p_j + u_j - P_j^{\text{nor}})$ in which we replace $p_j + u_j$ with its expression in Eq. (18). We finally obtain q_j as a non linear function of d_j

$$q_j = q_j^{\text{nor}} - \lambda_j^R \cdot (P_j^{\text{nor}} / 2\gamma_j) \times \left((1 - \gamma_j) \cdot d_j - \sqrt{(1 + \gamma_j)^2 \cdot d_j^2 - 4\gamma_j d_j^{\text{nor}} \cdot d_j} \right), \quad (19)$$

$$\forall p_{jt} + u_{jt} = p_j + u_j > P_j^{\text{nor}}, \quad t = S_j, \dots, S_j + d_j.$$

Obviously, $p_j + u_j$ in Eq. (18) has little chance to be an integer, in which case we can round its value and complete with overtime to meet the work content. To illustrate, let us consider our example in Section 3.1.3 with parameters values $q_j^{\text{nor}} = 1$, $\lambda_j^R = 0.025$ and $\lambda_j^O = 0.00625$. Table 2 provides the values of quality q_j for the same manpower allocations as those in Table 1. We extended the computations to lower values of duration, $d_j = 4, 3$,

Fig. 4. Relationship between quality and duration.

in order to better emphasize the concavity of the relationship between quality and duration when overmanning is mainly utilized. In column “Add. workers”, we report the sum $\sum_{t=1}^{d_j} (p_{jt} + u_{jt} - P_j^{\text{nor}} + h_{jt} / H_R)$. For instance, for a reduced duration $d_j = 7$ obtained with overmanning mainly with $(p_{jt} + u_{jt} - P_j^{\text{nor}})_{t=1..7} = (0, 0, 0, 0, 1, 1, 1)$, this sum equals 3.3429 which corresponds to one additional worker for 3 days and a total of $0.3429 \times 8 = 2.7432$ overtime hours. Using Eq. (17), we have $q_j = 1 - 3\lambda_j^R - 2.7432\lambda_j^O = 0.9079$. Let us note that a duration $d_j = 7$ can also be obtained with $(p_{jt} + u_{jt} - P_j^{\text{nor}})_{t=1..7} = (0, 0, 0, 0, 0, 2, 1)$, which has a work content of 23.6001, and overtime hours equal to $(24 - 23.6001) \times 8 = 3.1992$. The corresponding quality is lower, with $q_j = 1 - 3\lambda_j^R - 3.1992\lambda_j^O = 0.9050$. But such an allocation of additional manpower can be optimal if no additional worker is available on the fifth day. With overtime only, duration $d_j = 7$ is obtained by utilizing $3 \times 8 = 24$ overtime hours and a quality $q_j = 1 - 24\lambda_j^O = 0.85$.

To reach a duration $d_j = 4$ with overmanning mainly, Eq. (18) gives $p_j + u_j = 6.71$. We therefore set $p_{jt} + u_{jt} = 7$ in the first 2 days and $p_{jt} + u_{jt} = 6$ in the last 2 days. The associated work content is equal to 23.3719, so we add $(24 - 23.3719) \times 8 = 5.0248$ overtime hours. The corresponding quality is $q_j = 1 - 14 \times 0.025 - 5.0248 \times 0.00625 = 0.6186$. For a duration $d_j = 3$, Eq. (18) provides $p_j + u_j = 9.99$. The manpower allocation (10,10,9) has a work content equal to 23.4581 so $(24 - 23.4581) \times 8 = 4.3352$ overtime hours are utilized. The quality q_j drops to 0.4729.

Fig. 4 plots the quality q_j as a function of the duration d_j for the two types of allocation displayed in Table 2. When overmanning is mainly used, the relationship between q_j and d_j is concave as illustrated in this Figure.

3.3. Optimization program

One method for solving multi-objective optimization problems is the lexicographic approach which requires an ordinal ranking of the achievement functions. The approach proceeds iteratively, solving first the most important objective as a single-objective problem. The second objective is then solved in which the optimal solution obtained in the previous step is added as a new constraint. The process is repeated until the whole sequence of single-objective optimization problems is solved Stadler (1988) for

a reference book and Russell and Taghipour (2019) for a recent application in scheduling).

This optimization approach is consistent with our planning problem where the objective functions of makespan $C_{\max}$, total cost B , and overall quality losses L are ranked in this order of importance to the decision maker. The method therefore consists of solving sequentially the following single-objective optimization problems: (1) $\min C_{\max}$; (2) $\min B$ subject to $C_{\max} \leq C_{\max}^*$ where $C_{\max}^*$ is the optimal value of (1); (3) $\min L$ subject to $C_{\max} \leq C_{\max}^*$ and $B \leq B^*$ where B^* is the optimal value of (2).

3.3.1. Preprocessing

The bounds of the set $\mathcal{T}_j = \{ES_j, \dots, LF_j\}$ are computed as follows. The earliest start time ES_j is defined as $ES_j = \max_{i \in \Gamma^{-1}(j)} \{ES_i + d_i\}$ where d_j is a lower bound on the processing time. This bound is obtained by hypothetically allocating the maximum of additional manpower to activity j , that is $d_j = \lceil P_j^{\text{nor}} \cdot d_j^{\text{nor}} / (W_j^R(P_j^{\text{max}}) + (H_0/H_R) \cdot P_j^{\text{nor}}) \rceil$. We set $ES_0 = 0$ and the earliest start time of dummy activity $n+1$ (end of the project) is a lower bound $\underline{C}_{\max}$ on the project completion time, $\underline{C}_{\max} = ES_{n+1}$.

The latest finish time LF_j is based upon normal processing times. We first compute the earliest start time in the normal mode $ES_j^{\text{nor}} = \max_{i \in \Gamma^{-1}(j)} \{ES_i^{\text{nor}} + d_i^{\text{nor}}\}$ with $ES_0^{\text{nor}} = 0$. The latest start time is then determined, with $LS_j^{\text{nor}} = \min_{i \in \Gamma(j)} \{LS_i^{\text{nor}}\} - d_j^{\text{nor}}$ and $LS_{n+1}^{\text{nor}} = ES_{n+1}^{\text{nor}}$. We finally obtain $LF_j = LS_j^{\text{nor}} + d_j^{\text{nor}}$. The latest finish time of activity $n+1$ simply corresponds to the project completion time in the normal mode, $C_{\max}^{\text{nor}}$, and constitutes an upper bound to the makespan $C_{\max}$. We have $C_{\max}^{\text{nor}} = LF_{n+1}$.

The total number of permanent workers with skill k dedicated to the project must allow for its execution in the normal mode and is thus computed as

$$P_k = \max_{t=1, \dots, C_{\max}^{\text{nor}}} \left(\sum_{\{j \in V_k | t \in \{ES_j^{\text{nor}}, \dots, ES_j^{\text{nor}} + d_j^{\text{nor}}\}\}} P_j^{\text{nor}} \right), \quad \forall k = 1, \dots, K.$$

3.3.2. Formulation

The first objective is to minimize the project completion time $C_{\max}$ with

$$C_{\max} \geq t \cdot z_{jt} \quad \forall j = 1, \dots, n, \quad t \in \mathcal{T}_j, \quad (20)$$

and

$$C_{\max} \leq C_{\max} \leq C_{\max}^{\text{nor}}. \quad (21)$$

Without loss of generality, we assume that the cost of one hour of permanent work, c_p , is identical for all skills. The same holds for the cost c_U of one hour of temporary work and the cost c_O of one hour of overtime. The second objective to be minimized under the optimal project duration constraint is the total cost B defined as the sum of the cost of permanent work, temporary work and overtime

$$B = \sum_{j=1}^n \sum_{t \in \mathcal{T}_j} (c_p \cdot H_R \cdot p_{jt} + c_U \cdot H_R \cdot u_{jt} + c_O \cdot h_{jt}). \quad (22)$$

The third objective is to minimize the project overall quality losses L under optimal duration and cost of the project, with

$$L = \sum_{j=1}^n \left(\sum_{l=0}^{P_j^{\text{max}}} L_j^R(l) \cdot y_{jlt} + \lambda_j^0 \sum_{t \in \mathcal{T}_j} h_{jt} \right), \quad (23)$$

and values of quality losses $L_j^R(l)$ computed beforehand using Eq. (14).

Precedence constraints state that activities can not start before completion of their predecessor activities

$$\sum_{\tau \in ES_j} z_{j\tau} \leq d_j^{\text{nor}} \cdot (1 - z_{it}) \quad \forall j = 1, \dots, n, \quad i \in \Gamma^{-1}(j), \quad t \in \mathcal{T}_i \cap \mathcal{T}_j. \quad (24)$$

Nonpreemption constraints ensure that activities execution can not be interrupted and restarted later. They apply to any activity j with a normal duration $d_j^{\text{nor}} \geq 2$ and such that $LF_j - ES_j \geq 3$ otherwise interruption can never occur

$$\begin{aligned} \sum_{\tau=t+1}^{LF_j} z_{j\tau} + d_j^{\text{nor}} (z_{jt} - z_{jt+1}) &\leq d_j^{\text{nor}} \\ \forall j &= 1, \dots, n, \quad \text{with } d_j^{\text{nor}} \geq 2, \\ \forall t &= ES_j, \dots, LF_j - 3 \quad \text{with } LF_j - ES_j \geq 3. \end{aligned} \quad (25)$$

Workforce requirement. The number of workers allocated to any activity j over its processing periods must satisfy its work content

$$\sum_{t \in \mathcal{T}_j} \left(\sum_{l=0}^{P_j^{\text{max}}} W_j^R(l) \cdot y_{jlt} + h_{jt}/H_R \right) = P_j^{\text{nor}} \cdot d_j^{\text{nor}} \quad \forall j = 1, \dots, n, \quad (26)$$

where values of $W_j^R(l)$ are computed beforehand using Eq. (4) and h_{jt}/H_R is the equivalent number of regular workers corresponding to the volume of overtime hours. Constraints on binary variables y_{jlt} in Eq. (5) and (6) are added to the optimization program.

Resources availability. For each skill k the number of permanent workers allocated to the execution of activities requiring that skill in each period should not exceed the total permanent workforce with skill k dedicated to the project

$$\sum_{j \in V_k} p_{jt} \leq P_k \quad \forall k = 1, \dots, K, \quad t \in \bigcup_{j \in V_k} \mathcal{T}_j. \quad (27)$$

As in Heimerl and Kolisch (2010), we assume that only permanent workers can work overtime. Recalling that in each period the number of overtime hours per worker is limited to H_0 hours, the following constraints guarantee that there is enough permanent workers in each period to ensure overtime hours

$$\sum_{j \in V_k} h_{jt} \leq H_0 \sum_{j \in V_k} p_{jt} \quad \forall k = 1, \dots, K, \quad t \in \bigcup_{j \in V_k} \mathcal{T}_j. \quad (28)$$

Summation over activities in constraints (28) means that some permanent workers with skill k allocated in regular time to a given activity may work overtime on a different activity also requiring skill k .

Due to legal constraints, each permanent worker can not work more than H_{OW} hours overtime per week (5 days) which is written as

$$\sum_{\tau=t}^{t+4} \left(\sum_{\{j \in V_k | \tau \in \mathcal{T}_j\}} h_{j\tau} \right) \leq (1/5) \cdot H_{OW} \cdot \sum_{\tau=t}^{t+4} \left(\sum_{\{j \in V_k | \tau \in \mathcal{T}_j\}} p_{j\tau} \right), \quad (29)$$

$$\forall k = 1, \dots, K, \quad t = \min_{j \in V_k} ES_j, \dots, \max_{j \in V_k} LF_j - 4.$$

Constraints (29) consider the total amount of overtime hours (right hand side) performed by the average number of permanent workers active on each day of the week. Our model, as a planning model, does not consider each permanent worker individually as this should be the case for an operational model of allocating individuals to the execution of activities.

Organizational constraints. We assume that the number of permanent workers assigned to any activity in each period is at least equal to this number in the normal mode

$$p_{jt} \geq P_j^{\text{nor}} \cdot z_{jt} \quad \forall j = 1, \dots, n, \quad t \in \mathcal{T}_j. \quad (30)$$

This is a standard assumption (see for instance Naber & Kolisch, 2014). Besides, constraints (30) avoid situations where only temporary workers would be dedicated to the execution of an activity.

No more than P_j^{max} workers in regular working hours can be allocated to the execution of activity j in any period

$$p_{jt} + u_{jt} \leq P_j^{\text{max}} \cdot z_{jt} \quad \forall j = 1, \dots, n, \quad t \in \mathcal{T}_j. \quad (31)$$

In each processing period, workers overtime are never in an overmanning situation, which implies that their maximum number equals P_j^{nor} so that overtime hours can not exceed $P_j^{\text{nor}} \cdot H_0$

$$h_{jt} \leq P_j^{\text{nor}} \cdot H_0 \cdot z_{jt} \quad \forall j = 1, \dots, n, \quad t \in \mathcal{T}_j. \quad (32)$$

Constraints (32) also ensure that if there is no worker during regular hours ($z_{jt} = 0$) then overtime can not take place ($h_{jt} = 0$). Let us note that overtime hours can be performed by workers other than those who were dedicated to the activity during regular hours.

Quality constraints. When activity j is accelerated its quality q_j degrades with overmanning and overtime usage but must not fall below a threshold q_j^{min} corresponding to the rate of unacceptable flaws in the checklist. This is written as $q_j^{\text{nor}} - \sum_{t \in \mathcal{T}_j} (L_{jt}^R + L_{jt}^O) \geq q_j^{\text{min}}$. Using the linearization, we have

$$q_j^{\text{nor}} - \lambda_j^O \sum_{t \in \mathcal{T}_j} h_{jt} - \sum_{t \in \mathcal{T}_j} \sum_{l=0}^{P_j^{\text{max}}} L_j^R(l) \cdot y_{jlt} \geq q_j^{\text{min}} \quad \forall j = 1, \dots, n, \quad (33)$$

where values of $L_j^R(l)$ are computed beforehand according to Eq. (14).

It should be noted that our formulation is partly inspired by the first of the four MIP Models for resource-constrained project scheduling with flexible resource profiles (namely FP-DT1) developed by Naber and Kolisch (2014). We thus used z_{jt} to indicate the processing status of activity j in period t and this choice was motivated by the intuitive definition of such variables. Similarities between model FP-DT1 and our formulation are however limited to the objective of makespan minimization in Eq. (20) and precedence and nonpreemption constraints in Eq. (24) and Eq. (25), respectively.

4. Numerical results

We considered several projects taken from the literature as well as a case study of the production of a motor coach at Alstom. We first describe the instances and the experimental design that involves 2 phases (Section 4.1). In the first phase, our incentive is to show the ability of our MILP formulation to solve the instances of the case study generated in a full factorial design. With numerous instances, we can also provide an analysis of the trade-off between duration, cost and quality (Section 4.2). The second phase aims at assessing the efficiency of our MILP formulation when applied to other projects with specific combinations of parameters values defining easy and hard instances (Section 4.3).

4.1. Project types, parameters setting and experimental design

Project types. We considered 7 manufacturing projects. The first one is a case study of the production of a very high speed train

motor coach at Alstom, a world leader in integrated transport systems and headquartered in France.¹ The data were collected from the production plant in Belfort, France. The project includes 36 activities with 18 crashable ones (normal duration greater than one day and allowed quality losses). This case study was then extended by rendering the 36 activities all crashable. Next we added 4 activities to get a project with 40 crashable activities.

The other projects come from the literature. We considered a robot type palletizing system installation with 18 activities (Kim, Kang, & Hwang, 2012). A typical construction project of a two-story building with 18 activities was taken from Mohammadipour and Sadjadi (2016). Finally, we took 2 instances from PSPLIB (Kolisch & Sprecher, 1996) with 30 activities and an average number of successors per activity of 1.5 and 2.125 respectively.

Skills, number of workers and normal processing times

The production of the train motor coach requires $K = 7$ skills (welding; painting; assembly; wiring; electricity; pneumatic; electronic automation). Any activity is processed on a single workstation and each workstation hosts workers with a single skill only (workstations do not mix skills). Alstom provided for each activity j , the number of workers P_j^{nor} ; the maximum number of workers P_j^{max} and the normal processing time d_j^{nor} .

For the other projects, specialties $k = 1..K$ and number of permanent workers $P_j^{\text{nor}}, P_j^{\text{max}}$ were set to consistent values with respect to the number of activities, their description if any, and their processing times.²

Minimum level of individual quality. Minimum quality levels can be derived from the number of unacceptable flaws in quality control inspection checklists. For our case study, we could obtain these checklists. An example of such a list is provided for the activity of the motor coach painting ($j = 6$) in Table 6 in Appendix B. The checklist contains 9 items among which 3 minor defects do not need rework (item 3: small localized painting defect; item 7: invisible paint peel-off; item 8: light scratches paint). We thus set $q_6^{\text{min}} = 2/3$. Testing activities such as pneumatic testing or safety equipments testing can not be accelerated: those with a normal duration $d_j^{\text{nor}} = 1$ and those for which not a single flaw is acceptable, that is $q_j^{\text{min}} = q_j^{\text{nor}} = 1$. These activities are testing activities.

For the robotic palletizing system, we took the minimum quality levels q_j^{min} as evaluated by the authors (Kim et al., 2012). For the other projects, three minimum quality levels (0.95, 0.80 and 0.67) were randomly assigned to each activity.

Costs and working time. Using the informations provided by Alstom, we set for all projects $c_P = 22.52$ euros; $c_U = 1.20c_P$ and $c_O = 1.25c_P$. In accordance with French law, we have for each worker $H_R = 7.8$ regular hours a day, $H_0 = 4$ overtime hours a day and $H_{OW} = 8$ hours a week.

Impact of overmanning on productivity (γ_j) and unit quality losses (λ_j^R, λ_j^O). Observations of processing times and quality levels in specific conditions of overmanning and overtime utilization would allow for an estimation of parameters γ_j, λ_j^R and λ_j^O as explained in Appendix C. Unfortunately, Alstom does not record such data and to the best of our knowledge, there is no empirical study that quantifies such impacts. Consequently, we adopted a simulation approach. In order to set consistent values for these parameters and to account for a wide variety of situations, we developed the following reasoning. In Section 3.1.1, we have shown that function $W_j^R(p_{jt} + u_{jt})$ reaches its maximum value for $p_{jt} + u_{jt} = (1 + \gamma_j)P_j^{\text{nor}}/2\gamma_j$. Thus, to allow for a maximum number of workers

¹ <https://www.alstom.com/company>.

² Data are available from the corresponding author upon request.

Table 3
Projects and experiment.

Project description	Robot type palletizing	Random, PSPLIB	Alstom 18 crashable activities	Random, PSPLIB	Two-story building	Alstom 36 crashable activities	Alstom 40 crashable activities
Reference	Kim et al. (2012)	Kolisch and Sprecher (1996)	This paper	Kolisch and Sprecher (1996)	Mohammadipour and Sadjadi (2016)	This paper	This paper
# Activities	18	30	36	30	18	36	40
Avg # succ.	1.105	1.5	10.26	2.125	1.3	1.026	1.0124
Duration(days)	27	37	107	54	121	119	131
#Variables	1155	4882	5553	6143	6483	8872	10193
#Constraints	1366	4149	6241	5764	6984	9144	10533
Phase 1 (all param. values)			×				
Phase 2 (easy and hard)	×	×		×	×	×	×

in regular hours $P_j^{\max}$ in each processing period, parameter γ_j must be such that $\gamma_j \leq P_j^{\text{nor}} / (2P_j^{\max} - P_j^{\text{nor}})$. We thus set $\gamma_j \equiv \gamma_j(\psi) = \psi \cdot P_j^{\text{nor}} / (2P_j^{\max} - P_j^{\text{nor}})$, with $\psi \in \{0.05, 0.20, 0.40, 0.60, 0.80, 1.00\}$ to represent an extensive range of productivity losses scenarios, starting with a negligible impact of overmanning on productivity and ending with a maximum impact.

It is reasonable to assume that companies limit the maximum number of workers on any activity so as to avoid rework. Thus, with $P_j^{\max}$ workers allocated to activity j over its whole processing time d_j , the quality should not drop below $q_j^{\min}$. We have $d_j = d_j(P_j^{\max}) = (P_j^{\text{nor}} \cdot d_j^{\text{nor}}) / W_j^R(P_j^{\max})$, where $W_j^R(P_j^{\max})$ is computed using Eq. (4) with $\gamma_j \equiv \gamma_j(\psi)$. The corresponding quality q_j is $q_j = q_j^{\text{nor}} - \lambda_j^R \cdot d_j(P_j^{\max}) \cdot (P_j^{\max} - P_j^{\text{nor}})$ and imposing $q_j \geq q_j^{\min}$ leads to $\lambda_j^R \leq (q_j^{\text{nor}} - q_j^{\min}) / (d_j(P_j^{\max}) \cdot (P_j^{\max} - P_j^{\text{nor}}))$. We thus set $\lambda_j^R \equiv \lambda_j^R(\varphi) = \varphi \cdot (q_j^{\text{nor}} - q_j^{\min}) / (d_j(P_j^{\max}) \cdot (P_j^{\max} - P_j^{\text{nor}}))$, with parameter φ in the same set of values as parameter ψ . In this way, we examine a wide range of scenarios where for example overmanning can strongly impact the productivity with a slight effect on quality (workers may work slowly while delivering high quality work) and conversely, workers may work fast (low value of ψ) with a low quality outcome (high value of φ).

As stated by Li et al. (2000), the negative impact on quality of overtime hours is about twice that of overmanning hours (see Eq. (11)). Managers of Alstom confirmed this order of magnitude but were unable to provide a sharper estimate. We thus adopted again a simulation approach, with $\lambda_j^O \equiv \lambda_j^O(\rho) = \rho \cdot \lambda_j^R(\varphi) / H_R$ and $\rho \in \{1.8, 1.9, 2.0, 2.1, 2.2\}$.

Experimental design. Our MILP was coded in C and linked with the CPLEX callable optimization library version 12.5. The experiments were executed on an Intel Xeon E5-2430 with a 2.20 gigahertz (16 Cores) CPU and 30 gigabytes RAM running the GNU/Linux Debian 7 operating system.

The experiment was divided into 2 phases. In the first phase, we considered the original case study with 36 activities and 18 crashable ones, with all combinations of parameters values. We thus solved 180 instances in order to analyze the trade-off between duration, cost and quality. We set a runtime limit for CPLEX to 3600 seconds throughout, for each of the three objectives to optimize consecutively. From the results we identified specific combinations of parameters values ψ and φ for which the solution time was minimum (easy instances) and maximum (hard instances). Thus, in the second phase, our intent is to study the efficiency of the MILP formulation over easy and hard instances for the 6 additional projects. For easy instances, we kept a time limit of 3600 seconds for each subproblem. For hard instances, the time limit was increased to 7200 seconds. Beyond a certain number of variables, we provided CPLEX with a starting solution. Table 3 summarizes the projects and experiment.

4.2. First phase: analysis of the trade-off between duration, cost and quality in our case study

Table 7 in Appendix B displays the data provided by Alstom for each activity $j = 1..36$ of the project: description; set $\Gamma^{-1}(j)$ of predecessor activities; skill k ; normal duration d_j^{nor} ; and minimum quality level $q_j^{\min}$. Applying all combinations of parameters values to the project, we obtained $6 \times 6 \times 5 = 180$ instances, solving for each of them 3 optimization programs (lexicographic approach).

We obtained high quality solutions with optimal durations in all cases, cost values within 0.01% of optimum (average gap to best bound equals 0.006%) and all quality values but four within 0.1% of optimal (the average gap to best bound equals 1.39% over these 4 cases, and 0.08% over all instances). It took on average 3 minutes in real time to solve one instance.

Results for the 180 instances are reported in Tables 8 and 9 in Appendix D where the first four columns describe the instance (instance number, impact of overmanning on productivity ψ , impact of overmanning on quality φ and factor ρ of the impact on quality of overtime compared with overmanning). The next three columns provide the duration reduction, cost increase and quality loss compared with the normal execution mode. In the normal mode, the project makespan is 107 days, with a labor cost of 60952.63 euros and a quality of 1. The labor cost is the cost of 347 days of permanent work of all specialities at a unit cost $c_p = 22.52$ euros per hour, with 7.8 regular hours a day ($347 \times 7.8 \times 22.52 = 60952.63$ euros).

Considering for example instance #1 in Table 8, the project makespan reaches its highest reduction of 16.82% (18 days) at the expense of a cost increase of 2.74% and a quality loss of 0.43%. The last three columns provide the savings of permanent workers in hours due to the project acceleration compared with the 347 days of permanent work required in the normal mode as well as the number of temporary and overtime hours. Thus, in instance #1, the project is completed using 313 days of permanent work instead of 347 which represents a saving in permanent hours of $34 \times 7.8 = 265.2$ with a use of 23 days of temporary work that is $23 \times 7.8 = 179.4$ hours, and 99.3 overtime hours.

Reductions in duration vary from 18 days to 3 days only when overmanning has the strongest impact on quality and productivity. Identical durations and costs were obtained for all $\varphi \leq 0.40$, except in 2 situations only over 90 cases.³ This shows that as long as the impact of overmanning on quality is low, only the effect of overmanning on productivity matters.

In order to better visualize the trade-off between duration and quality, results are rescaled to their maximum value in Fig. 5. The

³ These 2 cases correspond to $\varphi = 0.40$, $\psi = 0.80$ and $\rho = 2.1$ and 2.2, with small variations of objective values.

Fig. 5. Duration reduction and marginal quality losses compared with maximum.

left hand side of Fig. 5 plots duration reductions compared with maximum, for each parameters value (for one ψ value, we have five points corresponding to the five values of ρ). When ϕ is moderate to high ($\phi \in \{0.60, 0.80\}$) as well as in situations where both ϕ and ψ have extreme values ($\phi = 1.00$ and $\psi \geq 0.80$), the project duration exhibits a sensitivity to ρ , due to a quite complex trade-off between the use of the different kinds of manpower to meet quality constraints.

On the right hand side of Fig. 5, we report the marginal quality loss per day of duration reduction and rescaled to the maximum. Highest marginal quality losses are associated with the lowest duration reductions (and conversely) due to high values of ϕ and ψ that limit acceleration which is made at the expense of important quality losses. Put another way, satisfying individual quality constraints with strong impacts of additional manpower limits duration reductions. On a global basis, as the impact ϕ of overmanning on quality increases quality losses also experience an increase. Parameter ρ also influences the results, outlining the need of a rather accurate estimate of this parameter.

The marginal cost per day of duration reduction is related to the use of additional manpower and to the savings in permanent work. We thus represent in Fig. 6 the evolution of the marginal cost (compared with maximum), and the marginal rates (per day of duration reduction and rescaled to their maximum) of savings in permanent work, utilization of temporary work, and overtime. The dotted blue line on the horizontal axis indicates the value of ψ for which temporary hours are greater than overtime hours.

For a weak impact of overmanning on quality ($\phi = 0.05 - 0.40$, top left hand side of Fig. 6), more temporary hours than overtime hours are used when overmanning has little influence on productivity ($\psi < 0.40$). As ψ increases above 0.40, hiring of temporary workers follows the same pattern as savings in permanent workers: when savings decrease, more permanent workers are available which entails a decrease in temporary work and conversely. Overtime continuously increases with ψ but the marginal rate of temporary hours reaches its maximum value for $\psi = 1$ because temporary work is needed to offset the higher negative impact of overtime hours on quality. As overtime is more expensive than

temporary work, the marginal cost is closely related to the use of overtime.

When the impact of overmanning on quality is medium ($\phi = 0.60$, top right hand side of Fig. 6), more overtime hours than temporary hours are used whatever the impact of overmanning on productivity. Again, hiring of temporary work increases as less permanent work is available. From $\psi \geq 0.40$ overtime usage closely follows permanent work savings. If overmanning strongly affects quality ($\phi = 0.80$, bottom left hand side of Fig. 6), results become very sensitive to ρ values especially when the impact of overmanning on productivity is moderate ($\psi \leq 0.40$). With additional regular time workers who work relatively fast but with a pretty low quality outcome, the model provides unsteady solutions with large variations of temporary work and overtime usage in an opposite fashion: an important rate of overtime usage is accompanied with a small rate of temporary utilization and conversely. Temporary work reaches its minimum value when $\psi = 0.60$ and then increases continuously with ψ . Meanwhile, overtime follows the same pattern as permanent work savings, reaching their maximum for identical parameters values.

When the impact of overmanning on quality is maximum ($\phi = 1.00$, bottom right hand side of Fig. 6), as long as $\psi \leq 0.60$, more temporary workers than overtime are used, reaching a high utilization rate. For $\psi = 0.40 - 0.60$ results are quite sensitive to ρ values with a volatile overtime utilization, following permanent work savings. For ψ high ($\psi \geq 0.80$) acceleration (3 or 5 days of reduction) is made with overtime only at the smallest marginal cost over all situations. Thus, it is still worth accelerating the project when overmanning strongly affects both the quality and the productivity, but with overtime only.

Our results show the complexity of the trade-off between temporary and overtime hours when quality constraints must be met. Results depend to a large extent on parameters values so the model provides various solutions with quite different usages of additional manpower. With such intertwined effects, one can hardly predict what would be best in terms of labour utilization. This values the contribution of our model for planning properly the different kinds of manpower and provides an incentive to managers

Fig. 6. Marginal costs and marginal rates of permanent workers savings, temporary work and overtime compared with their maximum.

for an accurate estimate of the impact of additional workforce on productivity and on quality.

4.3. Second phase: efficiency of the MILP formulation

From our case study, it appears that CPU times heavily depend on parameters values as shown in Fig. 7. The bottom part of this figure provides for each of the 180 instances the total CPU time, and the CPU time to solve each optimization subproblem. In 83% of the instances (149 out of 180), the CPU time to minimize the duration represents the largest proportion of the total time, with 74% of this total time on average. Next, about 10% of the

instances consume 57% of the total time to get the optimal cost value at a 0.01% tolerance level. More rarely (7% of the instances), the objective of minimizing quality losses at a tolerance of 0.1% takes the longest time to be solved (59% of the total time on average). The upper part of Fig. 7 plots the average total time over ρ -values, making clear the high variability of execution times with respect to parameters (ψ, φ) . This average reaches a minimum of 375.15 seconds for $(\psi, \varphi) = (0.2, 0.05)$ and a maximum of 2971.73 seconds for $(\psi, \varphi) = (0.8, 0.2)$. We thus selected these two pairs of parameters values in combination with the 5 values of ρ to define 5 easy to solve instances and 5 hard ones for each of the 6 additional projects.

Fig. 7. CPU times of the 180 instances based on the case study.

Fig. 8. CPU times of easy instances.

A time limit of 3600 s per objective to minimize was set for the 30 easy instances. CPLEX reached the optimal solutions in 28 cases out of 30 (at a tolerance level of 0.1% for the objective of minimizing quality losses). The average gaps to best bound equal 0.59%, 0.06% and 0.19% for each of the 3 subobjectives respectively, with an average CPU time of 2660.83 seconds per instance. Fig. 8 plots the CPU time to solve the 30 easy instances with respect to

the number of variables associated with each project. CPU times obviously increase with the problem size in a non-linear fashion, as shown by the power trend on the average solution times per project.

For hard instances, the time limit per subproblem was increased to 7200 seconds. Beyond a certain number of variables, it was necessary to provide CPLEX with a starting solution. For the

Table 4

Gap to best bound and execution times - all instances.

Project description	Robot type palletizing system	Random, PSPLIB	Alstom 18 cashable activities	Random, PSPLIB	Two-story building	Alstom 36 cashable activities	Alstom 40 cashable activities
EASY instances							
Duration Gap (%)	0	0	0	0	0	3.579	0
Cost Gap (%)	0	0.008	0.009	0.009	0.343	0.005	0.006
Quality Gap(%)	0	0.006	0.014	0.07	0.953	0.048	0.079
CPU(s)	2.729	349.967	375.153	1082.593	7551.496	3541.274	3436.961
HARD instances							
Duration Gap (%)	0	0	0	1.951	6.136	17.066	16.309
Cost Gap (%)	0	0.107	0.008	0.31	0.793	0.677	0.711
Quality Gap(%)	0	0.173	0.092	6.576	0.221	28.858	38.243
CPU(s)	2.824	12257.241	2961.73	20788.92	21660.524	18489.792	20266.814
OVERALL							
#instances	10	10	180	10	10	10	10
Duration Gap (%)	0	0	0	0.976	3.068	10.323	8.154
Cost Gap (%)	0	0.057	0.007	0.159	0.568	0.341	0.358
Quality Gap(%)	0	0.089	0.063	3.323	0.587	14.453	19.161
CPU(s)	2.777	6303.604	1534.138	10935.756	14606.01	11015.533	11851.888

first subproblem of minimizing the makespan, we used the normal mode as an initial solution (no temporary work and no overtime). For the second and third subproblem (cost and quality losses minimization), the starting solution was simply the solution CPLEX found to the previous subproblem. Table 4 provides the average gap to best bound and execution time over the hard instances, the easy ones, and over all instances. With less than 9000 variables and constraints (first five projects), our MILP formulation leads to quite good solutions, with average gaps to best bound less than 3% for the duration, and 0.6% for the cost and quality losses. For the last two projects (Alstom, 36 and 40 crashable activities), the average gap to best bound remains quite low for the cost but increases to about 10% for the duration and to 15–20% approximately for the quality losses. Beyond 10000 variables, our MILP could hardly be applied as we unsuccessfully tried to solve an instance with 45 activities (extension of our case study). This leaves room for developing a heuristic solution method when larger projects are considered.

5. Conclusion

We have developed a MILP formulation to the problem of planning single-skilled manpower with homogeneous and static efficiency to execute a project so as to lexicographically minimize the makespan, the total cost and quality losses while meeting constraints on individual qualities, resource availability as well as non-preemption and precedence constraints. The rationale for using only additional manpower to expedite the project relies on the fact that workstations (tools and equipment) remain unchanged in the mid-run. Our contribution is three-fold. This paper is the first to formulate a direct relationship between quality and labor utilization. Second, we consider productivity losses due to overmanning. Third, our model needs an estimate for only three parameters for each activity to obtain the cost, the quality and the duration

associated with an almost infinite number of execution modes, which makes its implementation in practice easier than multi-mode modeling approaches requiring parameters estimation in each activity execution mode.

The model provides the optimal allocation of permanent and temporary workers as well as overtime hours to each processing period of every activities where flexible resource profiles are assumed, which is consistent with project management practices in manufacturing environments. Based on a real project of a very high speed train motor coach at Alstom, 180 instances have been generated on which the model has been successfully implemented with optimal manpower allocation showing a complex trade-off between permanent work savings, temporary workers and overtime hours. Besides, we have shown the applicability of our model to other types of projects.

Future research includes an empirical study to establish the relationship between additional manpower (overtime and overmanning) and productivity on the one hand and between manpower and quality on the other hand, for several work types and manufacturing environments. The efficiency of other MIP formulations could be explored as in Naber and Kolisch (2014) and heuristic solution methods could be developed.

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Appendix A. Notations and definitions

Table 5
Notations and definitions.

Indices	
i, j	Activity
t, τ	Time period (day)
k	Skill
Parameters	
$V = \{0, \dots, n + 1\}$	Set of activities (n is the number of actual activities)
$\Gamma^{-1}(j), \Gamma(j)$	Set of activities immediately preceding j and succeeding j respectively
K	Number of different skills required for the project
V_k	Subset of activities requiring skill k
$p_j^{\text{nor}}, p_j^{\text{max}}$	Normal and max. number of workers with skill k on j in each period
d_j^{nor}	Normal processing time of activity j
γ_j	Impact of overmanning on productivity losses for activity j
$q_j^{\text{nor}}, q_j^{\text{min}}$	Normal quality and quality threshold for activity j
λ_j^R	Quality loss of j induced by one worker in overmanning for one period
λ_j^O	Quality loss of j associated with one overtime hour
H_R	Number of regular work hours per worker and period
H_O, H_{OW}	Max. number of overtime hours per worker, per day and per week resp.
c_P, c_U, c_O	Cost of one hour of permanent work, temporary work and overtime resp.
Computed parameters	
$\mathcal{P}_k$	Total number of workers with skill k dedicated to the project
d_j	Lower bound on the processing time of activity j
ES_j, LF_j	Earliest start time and latest finish time of activity j
$C_{\text{max}}^{\text{nor}}, C_{\text{max}}$	Upper and lower bounds on the makespan
$W_j^R(l)$	Work content of l workers on activity j , $l = 0..p_j^{\text{max}}$
$L_j^R(l)$	Quality loss associated with l workers on activity j , $l = 0..p_j^{\text{max}}$
Variables	
C_{max}	Project completion time
p_{jt}	Number of permanent workers allocated to j in period t (integer)
u_{jt}	Number of temporary workers allocated to j in period t (integer)
h_{jt}	Number of overtime hours assigned to j in period t (continuous)
z_{jt}	Binary equal to 1 if j is processed in period t and 0 otherwise
y_{jtl}	Binary equal to 1 if $p_{jt} + u_{jt} = l$ and 0 otherwise
Definitions	
$\mathcal{T}_j = \{ES_j, \dots, LF_j\}$	Set of feasible processing periods for activity j
$W_{jt}^R \equiv W_j^R(p_{jt} + u_{jt})$	Number of productive workers during r...egular hours on activity j in period t
$W_{jt}^O \equiv W_j^O(h_{jt})$	Number of productive workers during overtime hours on activity j in period t
$L_{jt}^R \equiv L_j^R(p_{jt} + u_{jt}; \lambda_j^R)$	Quality loss of j in period t due to overmanning
$L_{jt}^O \equiv L_j^O(h_{jt}; \lambda_j^O)$	Quality loss of j in period t due to overtime
q_j	Quality of activity j
L	Project quality loss
B	Project total cost
Parameters in the simulations	
ψ with $\gamma_j \equiv \gamma_j(\psi)$	General impact of overmanning on productivity in the company
φ with $\lambda_j^R \equiv \lambda_j^R(\varphi)$	General impact of overmanning on quality in the company
ρ with $\lambda_j^O \equiv \lambda_j^O(\rho)$	General impact of overtime on quality in the company

Appendix B. Data of the project at Alstom

Table 6
Quality control inspection checklist for activity $j = 6$: Motor coach painting.

Item #	Check point	Defect statement	Impact	Acceptability
1	Painting area	Overlap/Missing	Non compliance with customer specifications	No
2	Color hue	Major defect	Non compliance with customer specifications	No
3	Color hue	Small localized defect	Esthetics	Yes
4	Resin finishing	Non uniformity	Non compliance with customer specifications	No
5	Resin area	Missing	Non compliance with customer specifications	No
6	Paint finishing	Missing	Non compliance with customer specifications	No
7	Paint finishing	Invisible peel-off	Esthetics	Yes
8	Paint finishing	Light scratches	Esthetics	Yes
9	Paint composition	Wrong percentage of components	Non compliance with customer specifications	No

Table 7
Parameters of the project activities.

j	Description	$\Gamma^{-1}(j)$	k	d_j^{nor}	p_j^{nor}	p_j^{max}	q_j^{min}
0	Start	$\emptyset$	–	0	–	–	–
1	Girder welding	0	1	7	4	5	0.80
2	Lower chassis welding	1	1	7	4	5	0.80
3	Left lateral side mounting	2	1	7	3	4	0.80
4	Right lateral side mounting	3	1	7	3	4	0.80
5	Cabin assembly	4	1	8	3	4	0.80
6	Motor coach painting	5	2	10	3	4	0.67
7	Piping mechanical parts	6	3	4	4	5	0.80
8	High voltage pre-cabling	0	4	9	1	2	0.80
9	High voltage cabling	7, 8	3	1	4	4	0.80
10	Floor and ventilation ducts	9	3	1	4	4	0.80
11	Low voltage precabling	0	4	24	1	2	0.80
12	Low voltage cabling	10, 11	3	2	4	5	0.80
13	Front part cabling	12	3	1	2	2	0.80
14	Fairing and trapdoors equipment	12	3	1	3	3	0.67
15	Fairing and windscreen	13, 14	3	1	5	5	0.80
16	Driver desk and cabin covers	15	3	1	5	5	0.80
17	Cabinet partition and tools	16	3	1	5	5	0.80
18	Indoor section	17	3	2	5	6	0.80
19	Engine and underframe equipment	18	3	2	5	6	0.80
20	Cowls connection	19	5	6	1	2	0.80
21	Cowls equipment	19	5	6	1	2	0.67
22	Cowls mounting	20, 21	5	2	2	3	0.80
23	Cabling/balancing	22	5	1	2	2	0.80
24	Rooftop equipment	23	5	1	2	2	0.67
25	Air brake test	24	3	1	2	2	1.00
26	Chocks laying	25	3	1	2	2	0.67
27	Bogie mounting preparation	26	3	2	2	3	0.67
28	Bogie mounting and connection	27	3	2	2	3	0.80
29	Louvers	28	3	3	2	3	0.80
30	Low voltage test	29	5	11	2	2	1.00
31	High voltage test	30	5	2	2	2	1.00
32	Pneumatic test	31	6	4	2	2	1.00
33	Safety equipment test	32	7	5	2	2	1.00
34	Siemens supplies test	33	7	2	2	2	1.00
35	Dynamic test	34	7	1	2	2	1.00
36	Mechanical test	35	7	1	2	2	1.00
37	End	36	–	0	–	–	–

Legend. Skill $k = 1$: welding; $k = 2$: painting; $k = 3$: assembly; $k = 4$: wiring; $k = 5$: electricity; $k = 6$: pneumatic; $k = 7$: electronic automation.

Appendix C. Estimation of parameters

It can be possible to produce an estimate of coefficient γ_j by allocating a constant number of workers $p_j + u_j = p_j^{\text{nor}} + 1$ over processing periods and recording the resultant durations d_j^{obs} . Using Eq. (26) with no overtime hours, we would have $d_j^{\text{obs}} = (p_j^{\text{nor}} \cdot d_j^{\text{nor}}) / W_j^R(p_j^{\text{nor}} + 1)$. Replacing $W_j^R(p_j^{\text{nor}} + 1)$ by its expression in Eq. (4), we get $d_j^{\text{obs}} = p_j^{\text{nor}} \cdot d_j^{\text{nor}} / [(1 + \gamma_j) \cdot (p_j^{\text{nor}} + 1) - \frac{\gamma_j}{p_j^{\text{nor}}} \cdot (p_j^{\text{nor}} + 1)^2]$ that we can solve in γ_j to obtain an estimate $\hat{\gamma}_j = p_j^{\text{nor}} - ((p_j^{\text{nor}})^2 / (p_j^{\text{nor}} + 1)) \cdot (d_j^{\text{nor}} / d_j^{\text{obs}})$. Recording the observed quality q_j^{obs} in the same overmanning situation and using Eq. (10), we obtain $q_j^{\text{obs}} = q_j^{\text{nor}} - \lambda_j^R \cdot d_j^{\text{obs}}$ which provides an estimate $\hat{\lambda}_j^R = (q_j^{\text{nor}} - q_j^{\text{obs}}) / d_j^{\text{obs}}$.

Following a similar reasoning, it could be possible to record quality q_j^{obs} associated with a constant number of overtime hours h_j over processing periods and no overmanning. With Eq. (26), the

processing time d_j would equal $d_j = p_j^{\text{nor}} \cdot d_j^{\text{nor}} / (p_j^{\text{nor}} + h_j / H_R)$. Using Eq. (10), we get $q_j^{\text{obs}} = q_j^{\text{nor}} - \lambda_j^O \cdot d_j \cdot h_j$ which leads to $\hat{\lambda}_j^O = (q_j^{\text{nor}} - q_j^{\text{obs}}) / (d_j \cdot h_j)$. Obviously, repeating the experiment a large number of times would allow for sharper estimates.

Appendix D. Simulation results

Let us recall that parameter ψ reflects the impact of overmanning on productivity losses, parameter φ denotes the impact of overmanning on quality and parameter ρ measures the impact on quality of overtime relatively to overmanning ($\rho = 1.8$ for instance means that the impact of one overtime hour on quality is 1.8 times higher than the impact of one hour of overmanning on the quality). Blue shaded cells show that we have the same duration reductions and cost increases for $\varphi \in \{0.05, 0.20, 0.40\}$ and for each ψ and ρ values (except in 2 situations over 90 with $\psi = 0.80$; $\varphi = 0.40$ and $\rho \in \{2.1, 2.2\}$).

Table 8
Simulation results for instances #1 to #90.

Instance				Variation in %			Total number of hours		
#	ψ	φ	ρ	Duration	Cost	Quality	Perm. saving	Temporary	Overtime
1	0.05	0.05	1.8	-16.82	2.74	-0.43	265.2	179.4	99.3
2			1.9	-16.82	2.74	-0.43	265.2	179.4	99.3
3			2.0	-16.82	2.74	-0.44	265.2	179.4	99.3
4			2.1	-16.82	2.74	-0.45	265.2	179.4	99.3
5			2.2	-16.82	2.74	-0.46	265.2	179.4	99.3
6	0.20		1.8	-16.82	2.74	-1.71	265.2	179.4	99.3
7			1.9	-16.82	2.74	-1.74	265.2	179.4	99.3
8			2.0	-16.82	2.74	-1.77	265.2	179.4	99.3
9			2.1	-16.82	2.74	-1.79	265.2	179.4	99.3
10			2.2	-16.82	2.74	-1.82	265.2	179.4	99.3
11	0.40		1.8	-16.82	2.74	-3.42	265.2	179.4	99.3
12			1.9	-16.82	2.74	-3.47	265.2	179.4	99.3
13			2.0	-16.82	2.74	-3.53	265.2	179.4	99.3
14			2.1	-16.82	2.74	-3.59	265.2	179.4	99.3
15			2.2	-16.82	2.74	-3.65	265.2	179.4	99.3
16	0.60		1.8	-14.95	2.16	-4.70	202.8	101.4	111.7
17			1.9	-14.95	2.16	-4.80	202.8	101.4	111.7
18			2.0	-14.95	2.16	-4.89	202.8	101.4	111.7
19			2.1	-14.95	2.16	-4.99	202.8	101.4	111.7
20			2.2	-14.02	2.04	-4.52	195.0	101.4	102.9
21	0.80		1.8	-11.21	1.63	-4.35	156.0	109.2	55.2
22			1.9	-11.21	1.63	-4.41	156.0	109.2	55.2
23			2.0	-11.21	1.63	-4.32	156.0	124.8	40.3
24			2.1	-11.21	1.63	-4.37	156.0	124.8	40.3
25			2.2	-11.21	1.63	-4.41	156.0	124.8	40.3
26	1.00		1.8	-8.41	1.42	-3.76	140.4	124.8	23.3
27			1.9	-8.41	1.42	-3.79	140.4	124.8	23.3
28			2.0	-8.41	1.42	-3.82	140.4	124.8	23.3
29			2.1	-8.41	1.42	-3.85	140.4	124.8	23.3
30			2.2	-8.41	1.42	-3.89	140.4	124.8	23.3
31	0.20	0.05	1.8	-16.82	4.58	-0.48	265.2	171.6	146.5
32			1.9	-16.82	4.58	-0.49	265.2	171.6	146.5
33			2.0	-16.82	4.58	-0.50	265.2	171.6	146.5
34			2.1	-16.82	4.58	-0.51	265.2	171.6	146.5
35			2.2	-16.82	4.58	-0.52	265.2	171.6	146.5
36	0.20		1.8	-16.82	4.58	-1.90	265.2	171.6	146.5
37			1.9	-16.82	4.58	-1.95	265.2	171.6	146.5
38			2.0	-16.82	4.58	-1.99	265.2	171.6	146.5
39			2.1	-16.82	4.58	-2.03	265.2	171.6	146.5
40			2.2	-16.82	4.58	-2.08	265.2	171.6	146.5
41	0.40		1.8	-16.82	4.58	-3.81	265.2	171.6	146.5
42			1.9	-16.82	4.58	-3.89	265.2	171.6	146.5
43			2.0	-16.82	4.58	-3.98	265.2	171.6	146.5
44			2.1	-16.82	4.58	-4.07	265.2	171.6	146.5
45			2.2	-16.82	4.58	-4.15	265.2	171.6	146.5
Instance (continued)				Variation in %			Total number of hours		
#	ψ	φ	ρ	Duration	Cost	Quality	Perm. saving	Temporary	Overtime
46	0.20	0.60	1.8	-14.02	3.34	-4.56	195.0	101.4	130.9
47			1.9	-14.02	3.34	-4.67	195.0	101.4	130.9
48			2.0	-13.08	2.90	-4.60	171.6	62.4	140.2
49			2.1	-13.08	2.90	-4.72	171.6	62.4	140.2
50			2.2	-13.08	2.90	-4.83	171.6	62.4	140.2
51	0.80		1.8	-11.21	2.57	-5.05	156.0	70.2	113.1
52			1.9	-10.28	2.49	-4.81	156.0	85.8	96.4
53			2.0	-10.28	2.62	-4.76	156.0	109.2	76.8
54			2.1	-10.28	2.62	-4.85	156.0	109.2	76.8
55			2.2	-9.35	2.56	-4.30	156.0	117.0	67.9
56	1.00		1.8	-8.41	2.45	-4.36	140.4	117.0	53.0
57			1.9	-8.41	2.58	-4.26	140.4	140.4	33.5
58			2.0	-8.41	2.62	-4.19	140.4	148.2	26.7
59			2.1	-8.41	2.62	-4.23	140.4	148.2	26.7
60			2.2	-8.41	2.62	-4.27	140.4	148.2	26.7
61	0.40	0.05	1.8	-14.02	4.92	-0.45	234.0	85.8	211.3
62			1.9	-14.02	4.92	-0.46	234.0	85.8	211.3
63			2.0	-14.02	4.92	-0.48	234.0	85.8	211.3
64			2.1	-14.02	4.92	-0.49	234.0	85.8	211.3
65			2.2	-14.02	4.92	-0.51	234.0	85.8	211.3
66	0.20		1.8	-14.02	4.92	-1.78	234.0	85.8	211.3
67			1.9	-14.02	4.92	-1.84	234.0	85.8	211.3
68			2.0	-14.02	4.92	-1.90	234.0	85.8	211.3
69			2.1	-14.02	4.92	-1.96	234.0	85.8	211.3
70			2.2	-14.02	4.92	-2.02	234.0	85.8	211.3
71	0.40		1.8	-14.02	4.92	-3.56	234.0	85.8	211.3
72			1.9	-14.02	4.92	-3.68	234.0	85.8	211.3
73			2.0	-14.02	4.92	-3.80	234.0	85.8	211.3
74			2.1	-14.02	4.92	-3.92	234.0	85.8	211.3
75			2.2	-14.02	4.92	-4.04	234.0	85.8	211.3
76	0.60		1.8	-10.28	3.04	-3.86	210.6	46.8	189.3
77			1.9	-10.28	3.04	-4.02	210.6	46.8	189.3
78			2.0	-10.28	3.08	-4.15	202.8	46.8	184.0
79			2.1	-10.28	3.12	-4.28	195.0	46.8	178.7
80			2.2	-10.28	3.12	-4.43	195.0	46.8	178.7
81	0.80		1.8	-8.41	2.57	-4.19	210.6	54.6	171.8
82			1.9	-8.41	2.99	-4.28	210.6	85.8	150.8
83			2.0	-8.41	3.30	-4.36	210.6	109.2	135.1
84			2.1	-8.41	3.51	-4.44	210.6	124.8	124.7
85			2.2	-8.41	3.61	-4.53	210.6	132.6	119.4
86	1.00		1.8	-7.48	3.32	-4.49	187.2	124.8	101.9
87			1.9	-7.48	3.32	-4.63	187.2	124.8	101.9
88			2.0	-7.48	3.41	-4.70	171.6	124.8	91.3
89			2.1	-7.48	3.50	-4.74	156.0	124.8	80.7
90			2.2	-7.48	3.54	-4.81	148.2	124.8	75.4

Table 9
Simulation results for instances #91 to #180

Instance (continued)				Variation in %			Total number of hours		
#	ψ	φ	ρ	Duration	Cost	Quality	Perm. saving	Temporary	Overtime
91	0.60	0.05	1.8	-13.08	5.94	-0.44	179.4	54.6	219.6
92			1.9	-13.08	5.94	-0.46	179.4	54.6	219.6
93			2.0	-13.08	5.94	-0.47	179.4	54.6	219.6
94			2.1	-13.08	5.94	-0.49	179.4	54.6	219.6
95			2.2	-13.08	5.94	-0.50	179.4	54.6	219.6
96	0.20		1.8	-13.08	5.94	-1.76	179.4	54.6	219.6
97			1.9	-13.08	5.94	-1.82	179.4	54.6	219.6
98			2.0	-13.08	5.94	-1.88	179.4	54.6	219.6
99			2.1	-13.08	5.94	-1.94	179.4	54.6	219.6
100			2.2	-13.08	5.94	-2.00	179.4	54.6	219.6
101	0.40		1.8	-13.08	5.94	-3.52	179.4	54.6	219.6
102			1.9	-13.08	5.94	-3.64	179.4	54.6	219.6
103			2.0	-13.08	5.94	-3.76	179.4	54.6	219.6
104			2.1	-13.08	5.94	-3.88	179.4	54.6	219.6
105			2.2	-13.08	5.94	-4.00	179.4	54.6	219.6
106	0.60		1.8	-10.28	3.88	-3.94	202.8	54.6	193.9
107			1.9	-9.35	3.26	-3.81	210.6	54.6	186.7
108			2.0	-9.35	3.26	-3.96	210.6	54.6	186.7
109			2.1	-9.35	3.26	-4.11	210.6	54.6	186.7
110			2.2	-8.41	2.94	-3.69	210.6	54.6	179.7
111	0.80		1.8	-7.48	2.25	-3.72	187.2	31.2	168.5
112			1.9	-7.48	2.25	-3.89	187.2	31.2	168.5
113			2.0	-5.61	1.67	-2.92	124.8	31.2	106.1
114			2.1	-5.61	1.67	-3.03	124.8	31.2	106.1
115			2.2	-5.61	1.67	-3.14	124.8	31.2	106.1
116	1.00		1.8	-5.61	1.67	-3.37	124.8	31.2	106.1
117			1.9	-5.61	1.67	-3.51	124.8	31.2	106.1
118			2.0	-5.61	1.87	-3.66	109.2	31.2	98.0
119			2.1	-5.61	2.48	-3.74	62.4	31.2	73.6
120			2.2	-5.61	2.94	-3.69	46.8	46.8	56.2
121	0.80	0.05	1.8	-11.21	5.89	-0.40	202.8	70.2	222.5
122			1.9	-11.21	5.89	-0.42	202.8	70.2	222.5
123			2.0	-11.21	5.89	-0.43	202.8	70.2	222.5
124			2.1	-11.21	5.89	-0.45	202.8	70.2	222.5
125			2.2	-11.21	5.89	-0.46	202.8	70.2	222.5
126	0.20		1.8	-11.21	5.89	-1.61	202.8	70.2	222.5
127			1.9	-11.21	5.89	-1.67	202.8	70.2	222.5
128			2.0	-11.21	5.89	-1.73	202.8	70.2	222.5
129			2.1	-11.21	5.89	-1.79	202.8	70.2	222.5
130			2.2	-11.21	5.89	-1.85	202.8	70.2	222.5
131	0.40		1.8	-11.21	5.89	-3.21	202.8	70.2	222.5
132			1.9	-11.21	5.89	-3.34	202.8	70.2	222.5
133			2.0	-11.21	5.89	-3.46	202.8	70.2	222.5
134			2.1	-10.28	5.10	-3.02	195.0	70.2	199.1
135			2.2	-10.28	5.10	-3.12	195.0	70.2	199.1
136	0.80	0.60	1.8	-9.35	4.09	-3.73	210.6	70.2	189.7
137			1.9	-8.41	3.66	-3.31	210.6	70.2	180.3
138			2.0	-8.41	3.66	-3.44	210.6	70.2	180.3
139			2.1	-8.41	3.66	-3.57	210.6	70.2	180.3
140			2.2	-8.41	3.66	-3.70	210.6	70.2	180.3
141	0.80		1.8	-7.48	2.80	-3.70	187.2	46.8	165.4
142			1.9	-7.48	2.80	-3.86	187.2	46.8	165.4
143			2.0	-7.48	2.80	-4.02	187.2	46.8	165.4
144			2.1	-5.61	2.22	-3.03	124.8	46.8	103.0
145			2.2	-5.61	2.22	-3.13	124.8	46.8	103.0
146	1.00		1.8	-5.61	2.22	-3.40	124.8	46.8	103.0
147			1.9	-4.67	1.01	-2.73	109.2	0.0	109.2
148			2.0	-4.67	1.01	-2.87	109.2	0.0	109.2
149			2.1	-2.80	0.58	-1.89	62.4	0.0	62.4
150			2.2	-2.80	0.58	-1.98	62.4	0.0	62.4
151	1.00	0.05	1.8	-9.35	6.91	-0.32	187.2	109.2	194.5
152			1.9	-9.35	6.91	-0.33	187.2	109.2	194.5
153			2.0	-9.35	6.91	-0.34	187.2	109.2	194.5
154			2.1	-9.35	6.91	-0.35	187.2	109.2	194.5
155			2.2	-9.35	6.91	-0.36	187.2	109.2	194.5
156	0.20		1.8	-9.35	6.91	-1.26	187.2	109.2	194.5
157			1.9	-9.35	6.91	-1.31	187.2	109.2	194.5
158			2.0	-9.35	6.91	-1.35	187.2	109.2	194.5
159			2.1	-9.35	6.91	-1.40	187.2	109.2	194.5
160			2.2	-9.35	6.91	-1.44	187.2	109.2	194.5
161	0.40		1.8	-9.35	6.91	-2.53	187.2	109.2	194.5
162			1.9	-9.35	6.91	-2.62	187.2	109.2	194.5
163			2.0	-9.35	6.91	-2.71	187.2	109.2	194.5
164			2.1	-9.35	6.91	-2.79	187.2	109.2	194.5
165			2.2	-9.35	6.91	-2.88	187.2	109.2	194.5
166	0.60		1.8	-8.41	5.39	-3.38	210.6	109.2	180.4
167			1.9	-8.41	5.39	-3.51	210.6	109.2	180.4
168			2.0	-8.41	5.39	-3.63	210.6	109.2	180.4
169			2.1	-7.48	3.53	-3.18	187.2	62.4	166.4
170			2.2	-7.48	3.53	-3.30	187.2	62.4	166.4
171	0.80		1.8	-7.48	3.53	-3.79	187.2	62.4	166.4
172			1.9	-7.48	3.53	-3.94	187.2	62.4	166.4
173			2.0	-7.48	3.53	-4.09	187.2	62.4	166.4
174			2.1	-7.48	3.53	-4.24	187.2	62.4	166.4
175			2.2	-5.61	2.96	-3.23	124.8	62.4	104.0
176	1.00		1.8	-4.67	1.01	-2.43	109.2	0.0	109.2
177			1.9	-4.67	1.01	-2.57	109.2	0.0	109.2
178			2.0	-4.67	1.01	-2.70	109.2	0.0	109.2
179			2.1	-4.67	1.01	-2.84	109.2	0.0	109.2
180			2.2	-2.80	0.58	-1.85	62.4	0.0	62.4

References

- Afruzi, E. N., Najafi, A. A., Roghanian, E., & Mazinani, M. (2014). A multi-objective imperialist competitive algorithm for solving discrete time, cost and quality trade-off problems with mode-identity and resource-constrained situations. *Computers and Operations Research*, 50, 80–96.
- Alvanchi, A., Lee, S., & Abourizk, S. (2012). Dynamics of working hours in construction. *Journal of Construction Engineering and Management*, 138(1), 66–77.
- Babu, A., & Suresh, N. (1996). Project management with time, cost, and quality considerations. *European Journal of Operational Research*, 88, 320–327.
- Beckers, D. G. J., van der Linden, D., Smulders, P. G. W., Kompier, M. A. J., van Veldhoven, M. J. P., & van Yperen, N. W. (2004). Working overtime hours: Relations with fatigue, work motivation, and the quality of work. *Journal of Occupational and Environmental Medicine*, 46, 1282–1289.
- Broschak, J. P., & Davis-Blake, A. (2006). Mixing standard work and nonstandard deals: the consequences of heterogeneity in employment arrangements. *Academy of Management Journal*, 49(2), 371–393.
- Business Roundtable (BRT) (1980). Scheduled overtime effect on construction project, a construction industry cost effectiveness. *Procter and Gamble construction projects*.
- Circadian (2016). Staffing levels: A key to managing risk in 24/7 operations. Circadian Information LP.
- Cuyper, N. D., Jong, J. D., Witte, H. D., Isaksson, K., Rigotti, T., & Schalk, R. (2008). Literature review of theory and research on the psychological impact of temporary employment: towards a conceptual model. *International Journal of Management Reviews*, 10(1), 25–51.
- Fundeling, C. U., & Trautmann, N. (2010). A priority-rule method for project scheduling with work-content constraints. *European Journal of Operational Research*, 203, 568–574.
- Gibson, R. (2015). *Practical guide to disruption and productivity loss on construction and engineering projects*. Wiley-Blackwell.
- Gunduz, M. (2004). A quantitative approach for evaluation of negative impact of overmanning on electrical and mechanical projects. *Building and Environment*, 39(5), 581–587.
- Gunduz, M., & Hanna, A. S. (2005). Benchmarking change order impacts on productivity for electrical and mechanical projects. *Building and Environment*, 40, 1068–1075.
- Hanna, A. S., Chang, C.-K., Lackney, J. A., & Sullivan, K. T. (2007). Impact of overmanning on mechanical and sheet metal labor productivity. *Journal of Construction Engineering and Management*, 22–28.

- Hanna, A. S., & Sullivan, K. T. (2004). Impact of overtime on construction labor productivity. *Cost Engineering*, 46(4), 20–27.
- Hanna, A. S., Taylor, C. S., & Sullivan, K. T. (2005). Impact of extended overtime on construction labor productivity. *Journal of Construction Engineering and Management*, 734–739.
- Hartmann, S., & Briskorn, D. (2010). A survey of variants and extensions of the resource-constrained project scheduling problem. *European Journal of Operational Research*, 207(1), 1–14.
- Heimerl, C., & Kolisch, R. (2010). Scheduling and staffing multiple projects with a multi-skilled workforce. *Operations Research*, 32, 343–368.
- Hitchens, D. M., Wagner, K., & Birnie, J. E. (1992). Measuring the contribution of product quality to competitiveness: A note on theory and policy. *The Economic and Social Review*, 23, 455–463.
- Kaming, P. F., Holt, G. D., Kometa, S. T., & Olomolaiye, P. O. (1998). Severity diagnosis of productivity problems: a reliability analysis. *International Journal of Project Management*, 16, 107–113.
- Khang, D. B., & Myint, Y. M. (1999). Time, cost and quality trade-off in project management: a case study. *International Journal of Project Management*, 17, 249–256.
- Kim, J. Y., Kang, C. W., & Hwang, I. (2012). A practical approach to project scheduling: considering the potential quality loss cost in the time-cost tradeoff problem. *International Journal of Project Management*, 30, 264–272.
- Kolisch, R., & Sprecher, A. (1996). Psplib - a project scheduling problem library. *European Journal of Operational Research*, 96, 205–216.
- Li, H., Love, P. E. D., & Drew, D. S. (2000). Effects of overtime work and additional resources on project cost and quality. *Engineering, Construction and Architectural Management*, 7(3), 211–220.
- Liberatore, M. J., & Pollack-Johnson, B. (2013). Improving project management decision making by modeling quality, time, and cost continuously. *IEEE Transactions on Engineering Management*, 30, 518–528.
- Mahmud, A. (2015). Effects of worker fatigue on product quality: A case study in apparel industry. *International Journal of Scientific and Engineering Research*, 6, 1625–1632.
- Mechanical Contractors Association of America (MCAA) (2011). How to estimate the impacts of overtime on labor productivity. *MCAA Management Methods Manual, Bulletin No. OT1 Revised*, <http://tiac.ca/wp-content/uploads/2017/09/I-Change-Orders-Productivity-Overtime-A-Primer-for-the-Construction-Industry.pdf>.
- Mohammadipour, F., & Sadjadi, S. J. (2016). Project cost-quality-risk tradeoff analysis in a time-constrained problem. *Computers and Industrial Engineering*, 95, 111–121.
- Mungle, S., Benyoucef, L., Son, Y.-J., & Tiwari, M. K. (2013). A fuzzy clustering-based genetic algorithm approach for time-cost-quality trade-off problems: A case study of highway construction project. *Engineering Applications of Artificial Intelligence*, 26, 1953–1966.
- Naber, A., & Kolisch, R. (2014). Mip models for resource-constrained project scheduling with flexible resource profiles. *European Journal of Operational Research*, 239, 335–348.
- National Electrical Contractors Association (NECA) (1989). Overtime and productivity in electrical construction, <https://www.smacna.org/resources/resource/2016/08/22/neca-productivity-studies>.
- Orm, M. B., & Jeunet, J. (2018). Time cost quality trade-off problems: A survey exploring the assessment of quality. *Computers and Industrial Engineering*, 118, 319–328.
- Pencavel, J. (2014). The productivity of working hours. *The Economic Journal*, 125, 2052–2076.
- Rojas, E. M. (2008). *Construction productivity: A practical guide for building and electrical contractors*. J. Ross Publishing.
- Russell, A., & Taghipour, S. (2019). Multi-objective optimization of complex scheduling problems in low-volume low-variety production systems. *International Journal of Production Economics*, 208, 1–16.
- Stadler, W. (1988). *Multicriteria optimization in engineering and in the sciences*. Springer Science+Business Media, LLC.
- Tareghian, H. R., & Taheri, S. H. (2006). On the discrete time, cost and quality trade-off problem. *Applied Mathematics and Computation*, 181, 1305–1312.
- Thomas, H. R., & Raynar, K. A. (1997). Scheduled overtime and labor productivity: quantitative analysis. *Journal of Construction Engineering and Management*, 181–188.
- U.S. Army Corps of Engineers (1979). Modification Impact Evaluation Guide EP 415-1-3. Department of the Army.
- Weglarz, J., Jozefowska, J., Mika, M., & Waligora, G. (2011). Project scheduling with finite or infinite number of activity processing modes: A survey. *European Journal of Operational Research*, 208, 177–205.
- Yang, B., Guenes, J., & Brien, W. J. O. (2004). A heuristic approach for minimizing weighted tardiness and overtime costs in single resource scheduling. *Computers and Operations Research*, 31, 1273–1301.
- Zhang, L., Du, J., & Zhang, S. (2014). Solution to the time-cost-quality trade-off problem in construction projects based on immune genetic particle swarm optimization. *Journal of Management in Engineering*, 30, 163–172.