

## Multi-project and Procurement Scheduling for Manufacturing-to-order Environments under Price Inflation

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### Abstract

Production planning in manufacturing-to-order (MTO) environments has been treated by several researchers as a project scheduling problem, in which customers' orders are assumed to be different projects that rely on several shared resources. Processing several orders at the same time extends this problem to the resource-constrained multi-project scheduling problem (RCMPSP), while only single projects are considered in the relevant literature. A primary issue for this problem is procurement scheduling, which is handled using integrated project scheduling and material ordering (PSMO) models; however, existing PSMO models do not consider inflation-related costs caused by the ordering times for procurement items. In this paper, MTO production planning is modeled as a resource-constrained multi-project scheduling problem integrated with procurement scheduling under inflation. The proposed model reduced the delay by 72.7% on average and also reduced the delay penalties by 54% on average, compared to the current status of the case study.

**Keywords:** RCMPSP; Inflation; Preemption; MTO; PSMO.

### 1. Introduction

Manufacturing-to-order (MTO) companies produce highly customized products and work on simultaneous orders as multiple projects with the aim of meeting preset project objectives, e.g. time, cost, quality, technical requirements, and so on (Goli and Alinaghian, 2020). Production planning in these environments plays a vital role, since the project-based nature of the customers' orders adds complexity to the production planning problem (Goli et al., 2019).

Resource-constrained multi-project scheduling problem (RCMPSP) consists of multiple projects with their activities and precedence relations where activities need scarce resources. The goal is to construct a schedule that satisfies precedence and also resource constraints. Usually, project scheduling and material ordering are tackled autonomously. In other words, project schedule is developed by scheduling model, then resource requirements are calculated based on the generated schedule and ordering plan is determined based on resource requirements over time horizon. This procedure, ignores tradeoffs between ordering and holding costs. Consequently, the final solution is not optimal in terms of project total costs (Zoraghi et al., 2015). In order to overcome this issue, project scheduling and material ordering (PSMO) models are proposed by several researchers.

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Two main types of research studies have considered the MTO production environments by: (i) using hierarchical production planning approaches; and (ii) adapting the resource-constrained project scheduling problem (RCPSp) to tackle MTO production planning. Alfieri and Urgo (2015) have discussed the fact that existing hierarchical approaches do not consider entire phases of production at the same decision level, while project scheduling models can consider resource planning, scheduling, and procurement simultaneously at the same decision level. They suggested using RCPSp models for MTO production planning environments. This area is increasingly the topic of study in the relevant literature (Alfieri et al., 2011). Moreover, the integration of manufacturing and project management practices is required for the success of projects in MTO environments (Fraz et al., 2016). Hence, treating orders as projects will introduce project management concepts to the production environment, which can lead to increases in the probability of success.

Delays may threaten the success of the projects and result in direct and/or indirect costs and negative impacts on other project objectives, which can in itself cause disputes and claims (Assaf et al., 2019). Numerous causes of delays have been explored by researchers, and procurement-related issues have been mentioned in many relevant studies, e.g. Budayan (2019), Suppramaniam et al. (2018), Wei et al. (2018), Goodier et al. (2018), and Kadry et al. (2017). Procurement scheduling can reduce the project delays and cost overruns by providing the items required for project activities at the optimal time. Procurement scheduling is more important in countries with higher inflation rates, where late purchasing may increase procurement costs and thus project expenses. However, as-soon-as-possible purchasing not only needs large outlays of money in the initial phase of the project, but may also increase the inventory costs. It is therefore necessary to schedule the procurements optimally, so a part of our proposed model optimizes the procurement schedules regarding tradeoffs between ordering and holding costs.

The case examined in this paper is a factory that produces low- and medium-voltage busducts. A busduct contains several metal bars, and provides a reliable connection for transferring power to equipment at a certain voltage level. In our case study, the busducts are designed based on the desired features and then are produced based on the customer's requirements. Each order is considered as a project, so the factory works on several projects simultaneously. Several interruptions may occur during the production activities, based on project priorities and limitations on human resources and/or machines. A multi-project scheduling model that takes preemption into account is therefore developed for this case study. Factory contract records show frequent large delays in previous projects, which have imposed considerable penalties, and this formed our motivation for conducting this research.

In this paper, an integrated mathematical model is proposed which tackles multi-project and procurement scheduling simultaneously, with several considerations, e.g. renewable and nonrenewable resources, task preemption, inflation rate, inventory costs, etc.

The remaining sections of this paper are organized as follows: Section 2 presents an overview of the literature related to using project scheduling in production environments, and simultaneous project and procurement scheduling. The proposed mathematical model is discussed in Section 3. Section 4 presents numerical results and finally, Section 5 concludes the paper.

## **2. Literature review**

Figure 1 shows three related research areas where their intersections are coded by A to G. This paper is related to region C which is not considered by other researchers, to best of our knowledge. As the most-relevant research areas, regions A and B are considered here. In other words, this section reviews the most relevant literature in two areas: (i) using project scheduling approaches for MTO production planning (region A); and (ii) incorporating procurement scheduling into RCPSp (region B).

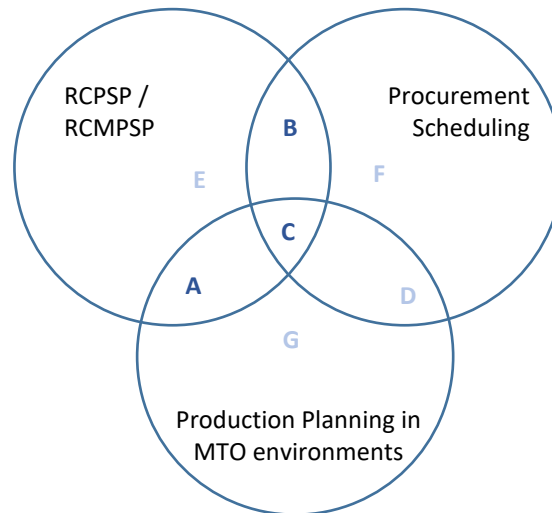


Figure 1. Relevant research areas

### 2.1. Adapting RCPSP models to MTO environments

Márkus et al. (2003) used a project scheduling approach for production planning, treating orders as projects competing for constrained resources. Their model aimed to create a production plan which satisfied all constraints with the minimum exceeded resource usages. They applied the model in two case studies. Egri et al. (2004) proposed a system that integrated a production planning model with a project scheduling model. The production planning model made aggregate plans in the long term, i.e. several months, while the scheduling model made short-term executable schedules which did not exceed the aggregate production plans or the resource capacity. Large-scale industrial cases were solved by the model and verified. Alfieri et al. (2011) proposed a project scheduling model for MTO production planning that took into account variable intensities for the activities. Generalized precedence relations were used for the precedence relationships of activities. Several random generated instances and an industrial case were tested, which demonstrated the viability of their model for small instances. Alfieri et al. (2012a) extended their previous research to consider uncertainty, and proposed a two-stage stochastic project scheduling model based on a scenario-based approach. Resource usages were considered as an uncertain parameter. They tested their model on several random generated instances and an industrial case. Alfieri et al. (2012b) aggregated production and material-requirements planning in MTO environments. Their model did not provide detailed scheduling but supported material requirements planning in the medium term. Alfieri and Urgo (2015) extended their previous work (Alfieri et al., 2011) to consider preemption by defining a new variable which determined the percentage of work done in each time bucket. Manzini and Urgo (2015) implemented a project scheduling approach for MTO environments with uncertain activity durations. They used their model to estimate the production time and to offer more realistic and competitive due dates to buyers. Two ideal and industrial cases were tested, which demonstrated the validity of their model.

Table 1 shows the above-mentioned researches. None of the above-mentioned research studies considered procurement scheduling, purchasing costs, or inventory costs. Moreover, the project scheduling approach used in all these studies optimized the process of working on only one project at a time or several projects one after another, rather than simultaneously. In contrast to existing research, our proposed model allows several projects to be worked on simultaneously, and takes into account procurement scheduling, purchasing costs, inflation, and inventory costs.

**Table 1.** Characteristics of researches adapted RCPSP models to MTO environments

Author(S)	Year	Number of projects	Solution approach	Other considerations
Márkus et al.	2003	Single	Branch-and-cut	Variable-intensity tasks and continuous resources
Egri et al.	2004	Single	Branch and cut	Aggregation
Alfieri et al.	2011	Single	CPLEX	GPRs and variable-intensity execution
Alfieri et al.	2012a	Single	Two-stage stochastic	Uncertainty in resource requirements
Alfieri et al.	2012b	Single	NA	GPRs and variable-intensity execution
Alfieri and Urgo	2015	Single	NA	Uncertainty in activity durations, GPRs, and variable-intensity
Manzini and Urgo	2015	Single	Graph-based algorithm	Uncertainty in activity durations
This paper	2020	Multiple	CPLEX	Activity preemption and material planning

## 2.2. Integrating project and procurement scheduling problems

Most research in the literature refers to this integrated problem as “project scheduling and material ordering (PSMO)”. Sabbagh and Salehi (2017) developed a mathematical model for integrating project scheduling with ordering decisions, for example the ordering time, and the quantity of materials required to be bought/produced for project activities. Sheikh-Sajadieh et al. (2009) proposed a genetic-based approach for project scheduling combined with materials ordering. Their model considered an all-unit discount policy for purchasing orders. Najafi et al. (2014) developed a model for project scheduling and material ordering problems, and their objective function minimized the total material inventory and ordering costs. Shahsavar et al. (2015) analyzed the impact of quantity discounts on project schedules and used a hybrid GA-PSO algorithm over numerous instances. Tabrizi and Ghaderi (2015a; 2016) developed a bi-objective formulation that minimized total costs and maximized schedule robustness against uncertainties. Tabrizi and Ghaderi (2015b) proposed a mathematical model which considered quantity discounts and space capacity. Zoraghi et al. (2017) examined a multi-mode PSMO problem including material purchasing and holding costs, in addition to a bonus/penalty resulting from the difference between the project completion time and its due date. Tabrizi (2018) and Habibi et al. (2019) added environmental and sustainability considerations to the PSMO problem, respectively.

Table 2 shows the above-mentioned researches. None of the above-mentioned papers considered the time value of money in purchasing; this aspect is modeled in the present paper by incorporating the inflation rate into calculations of purchasing costs. Few researchers have considered inventory costs. Moreover, all of the above-mentioned studies focused on only one project with non-preemptive activities, while our proposed model considers multiple projects with preemptive activities and takes inventory costs into account.

**Table 2.** Characteristics of PSMO researches

Author(S)	Year	Number of projects	Solution approach	Other considerations
Sheikh-Sajadieh et al.	2009	Single	Genetic algorithm	All-unit discount policy
Najafi et al.	2014	Single	Genetic algorithm	Perishable materials
Shahsavar et al.	2015	Single	Hybrid GA-PSO algorithm	Total-quantity discount policy
Tabrizi and Ghaderi	2015a	Single	$\epsilon$ -constraint method	All-unit discount
Tabrizi and Ghaderi	2015b	Single	CPLEX	Quantity discount and space availability restrictions
Tabrizi and Ghaderi	2016	Single	Differential evolution algorithm	Uncertainty in activity durations and execution costs
Sabbagh and Salehi	2017	Single	Genetic algorithm	-
Zoraghi et al.	2017	Single	PSO-GA algorithm	Multi-mode activities
Tabrizi	2018	Single	Non-dominated sorting genetic algorithm	Sustainability
Habibi et al.	2019	Single	NSGA-II and MOPSO	Sustainability
This paper	2020	Multiple	CPLEX	Inflation rate, preemption

Although many researchers have considered resource-constrained multi-project scheduling problem (RCMPSP), none of them has tackled MTO environments and/or procurement scheduling. More precisely, only single-project scheduling models exist that consider MTO environments or procurement scheduling. This paper tackles RCMPSP in an MTO environment and also considers procurement scheduling.

Compared to the researches reviewed in this section, the key contributions of this paper are:

- An integrated model is proposed for preemptive PSMO in a MTO production environment;
- Inflation is considered in project procurement scheduling;
- Multiple projects are considered, an aspect which is neglected in the relevant literature;

### **3. Proposed model**

#### **3.1. Case-study issues incorporated in the formulation of the model**

Without loss of generality, the proposed model is designed for a real-world case study, a factory that produces low- and medium-voltage busducts. Each customer's order is treated as a project, and several projects are typically in progress at any time. After a contract is signed, the electrical design is done based on the customer's requirements. After approving the design maps and a prepayment is made by the customer, procurement can be initiated. It should be noted that since each project needs specific materials with different features, they cannot be ordered before the design is approved.

The inflation rate in the country is considerable, and is approximately 18%, meaning that late purchasing will result in higher purchasing costs. On the other hand, as-soon-as-possible purchasing will result in higher inventory costs and higher outlays in the initial phases of projects, while customers pay the contract costs in several installments over the project lifecycle.

The availability of material resources is a function of procurement decisions. Preemption is allowed and is common in the case study considered here due to the approval periods, procurement delays, and limited capacities of the facilities and renewable resources.

Each project in this factory has a typical project network including 19 activities, as shown in Figure 2, and differ in terms of technical issues, e.g. busduct dimensions, materials, etc. Activity codes and titles are shown in Figure 2. There are 13 renewable resources, e.g. electrical engineers, CNC cutting machine, etc. and 63 nonrenewable resources, e.g. copper ingots, aluminum ingots, mono block, etc. Ten projects are considered in this case study, each for a specific customer.

The procurement process in this factory involves domestic and foreign purchasing, which may take from several days for items with a short lead time up to about a month for those with longer lead times.

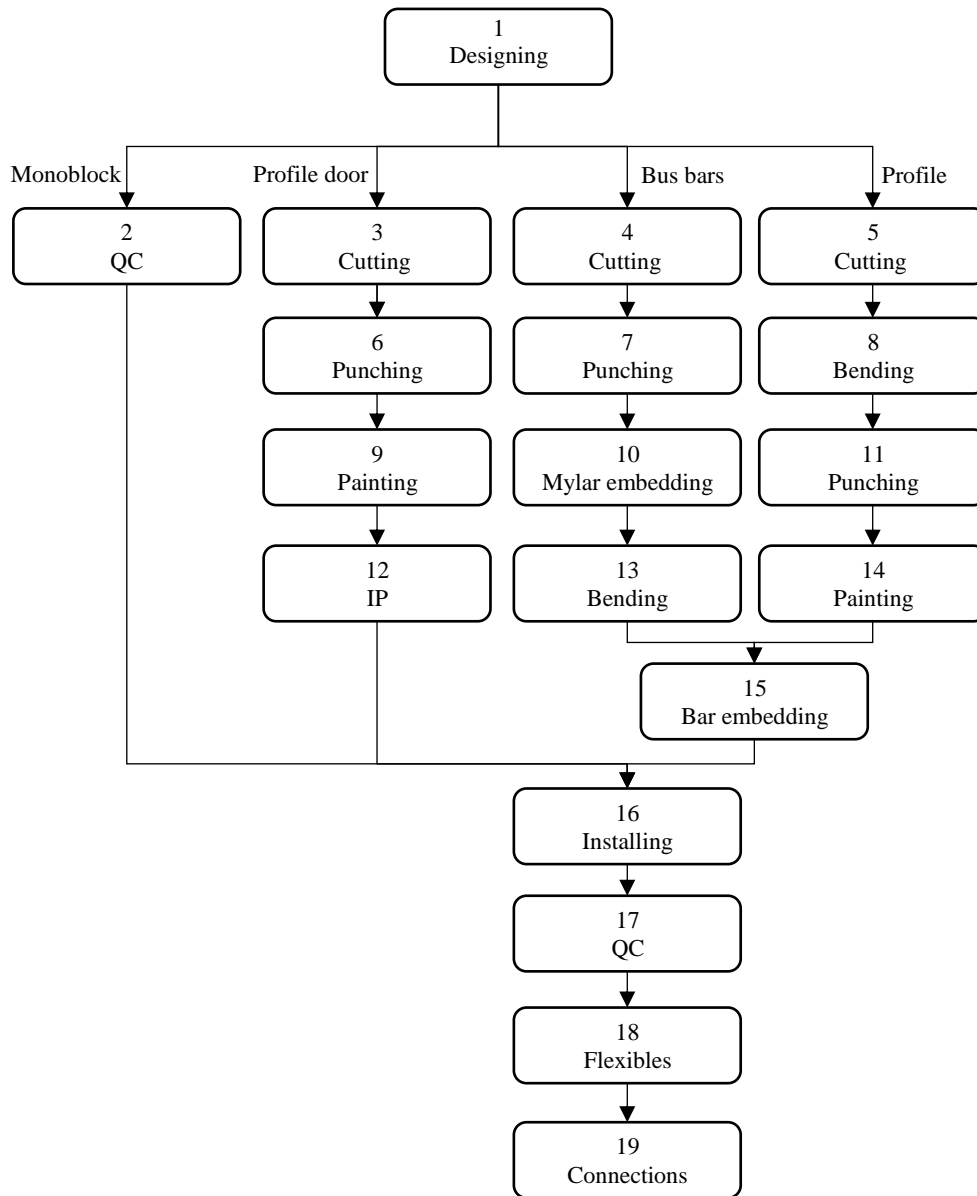


Figure 2. Project network for typical busduct manufacturing

The factory is located in Iran, which has a significant annual inflation rate and where prices rise day after day. The central bank forecasts an average rate of inflation for each year, but this usually exceeds the forecasts. For example, although the average inflation for the current year forecast was at 18%, higher values were experienced over several months compared to the same months of the previous year (Central Bank of Iran, 2019). Based on the opinions of top managers, three scenarios for annual inflation rate are considered: 18%, 23%, and 30%. We then calculate day-interval rates to be incorporated in the model.

### 3.2. Linking project and procurement scheduling variables

Instead of using separated variables for the ordering time, we define ordering time variables relative to activity starting-time variables. Figure 3 shows three possible strategies for the ordering time of each resource needed for an activity where // is used as axis break symbol.

Figure 3(a) shows an as-late-as-possible strategy used for purchasing, in which the required resource is ordered  $L_k$  time units sooner than the starting time of the related activity, where  $L_k$  represents the lead time of resource  $k$ . In this strategy, inventory costs will be minimized but purchasing costs may be increased due to continually rising prices.

Figure 3(b) shows an as-soon-as-possible strategy. In this strategy, the required resource is ordered after completion of the design activity. Purchasing costs will be minimized but inventory costs are maximized since items and materials are received long before they are needed.

Figure 3(c) shows a trade-off strategy in which a balance is found between inventory and purchasing costs by determining optimal values for the variables  $e$ . In other words, the required resource arrives  $e$  time units sooner than when it is required. This strategy can be converted into other strategies by using zero or maximum-available values for the variable  $e$ . The formulation of our model allows each of these three strategies to be used.

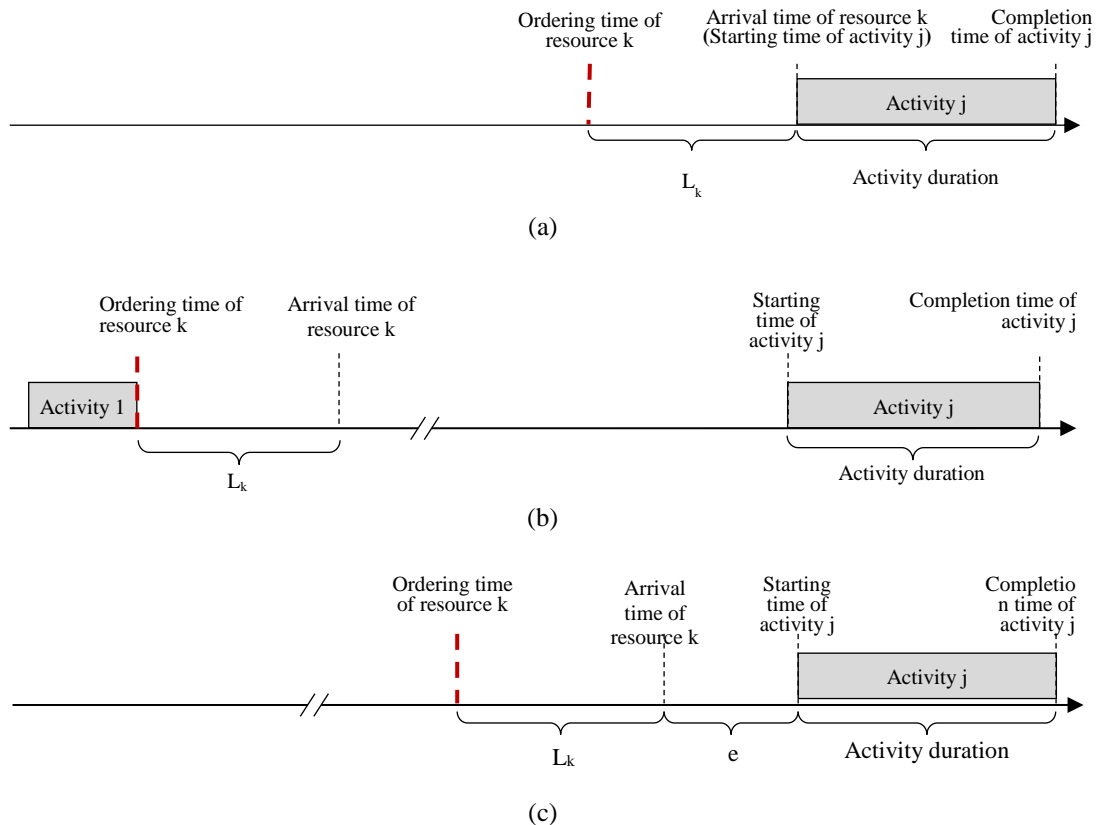


Figure 3. Possible strategies for ordering time for resource  $k$

### 3.3. Notation

Sets and parameters are indicated by capital letters, while lower-case letters are used for indices and variables.

#### Indices

$p$	Projects (customer's orders)
$i, j$	Project activities
$t, t'$	Periods of time
$k$	Nonrenewable resources
$k'$	Renewable resources
Sets	
$N_p$	Activities of project $p$

$A$  All of the precedence relations between pairs of activities, where  $(i, j)^p \in A$  indicates that activity  $i$  must be completed before activity  $j$  can be begun, and both activities belong to project  $p$

**Parameters**

- $D_{p,j}$  Duration of activity  $j$  of project  $p$
- $R_{pj k}$  Amount of nonrenewable resource  $k$  required by activity  $j$  of project  $p$
- $R'_{pj k'}$  Amount of renewable resource  $k'$  required by activity  $j$  of project  $p$
- $RR_{pj k}$  A binary variable that equals 1 if  $R_{p,j,k} > 0$ , 0 otherwise
- $U_{k'}$  Maximum amount of renewable resource  $k'$
- $T$  Planning horizon
- $L_k$  Lead time for purchasing nonrenewable resource  $k$
- $H_k$  Unit inventory cost related to nonrenewable resource  $k$  in each period of time
- $PR_{pk}$  Estimated unit price of nonrenewable resource  $k$  at the beginning of project  $p$
- $Due_p$  Due date of project  $p$
- $CD_p$  Penalty cost due to late completion of project  $p$  per each period of time
- $V_t$  Inflation coefficient if purchasing is carried out  $t$  intervals later than the project starting time
- $IR$  Calculated inflation rate for a given time unit
- $M$  A large number

**Decision variables**

- $x_{pjt}$  A binary variable that has the value 1 if activity  $j$  of project  $p$  is in progress at period  $t$ , and is 0 otherwise
- $s_{pj}$  Starting time for activity  $j$  of project  $p$
- $c_{pj}$  Completion time for activity  $j$  of project  $p$
- $e_{pj k}$  Number of time periods in which nonrenewable resource  $k$  arrives before the starting time of activity  $j$  of project  $p$
- $y_{pjkt}$  A binary variable that has the value 1 if a nonrenewable resource  $k$  is required for activity  $j$  of project  $p$  and is ordered at time  $t$ , and is 0 otherwise.
- $y'_{pjkt}$  A binary variable that has the value 1 if period  $t$  is the latest period of time in which nonrenewable resource  $k$  can be ordered to arrive by the starting time of activity  $j$  of project  $p$ , and is 0 otherwise
- $td_p$  Tardiness of project  $p$
- $z$  Objective function value

**3.4. Model formulation**

The proposed model is formulated in Eqs. (1)–(11), using the aforementioned notation. Equation (1) tries to minimize the tardiness penalties, inventory costs, inflation-related costs.

$$\begin{aligned}
 \text{Minimize } z = & \sum_p td_p CD_p \\
 & + \sum_p \sum_j \sum_k H_k R_{pj} e_{pj} \\
 & - \sum_p \sum_j \sum_k PR_{pk} R_{pj} \left( (1+IR)^{s_{pj}-L_k} - (1+IR)^{s_{pj}-L_k-e_{pj}} \right)
 \end{aligned} \tag{1}$$

In the third line of Eq. (1), inflation-related costs are incorporated via purchasing savings with a negative sign. Figure 3(a) depicts the purchasing cost for resource  $k$  when it is ordered at the latest possible time, while (b) shows the purchasing cost of resource  $k$  when it is ordered  $e_{pj}$  periods sooner than the latest possible time. The difference between these two figures represents the purchasing savings resulting from the earlier ordering time. This part of Eq. (1) is nonlinear, and will be substituted by a linear formulation, Eq. (1').

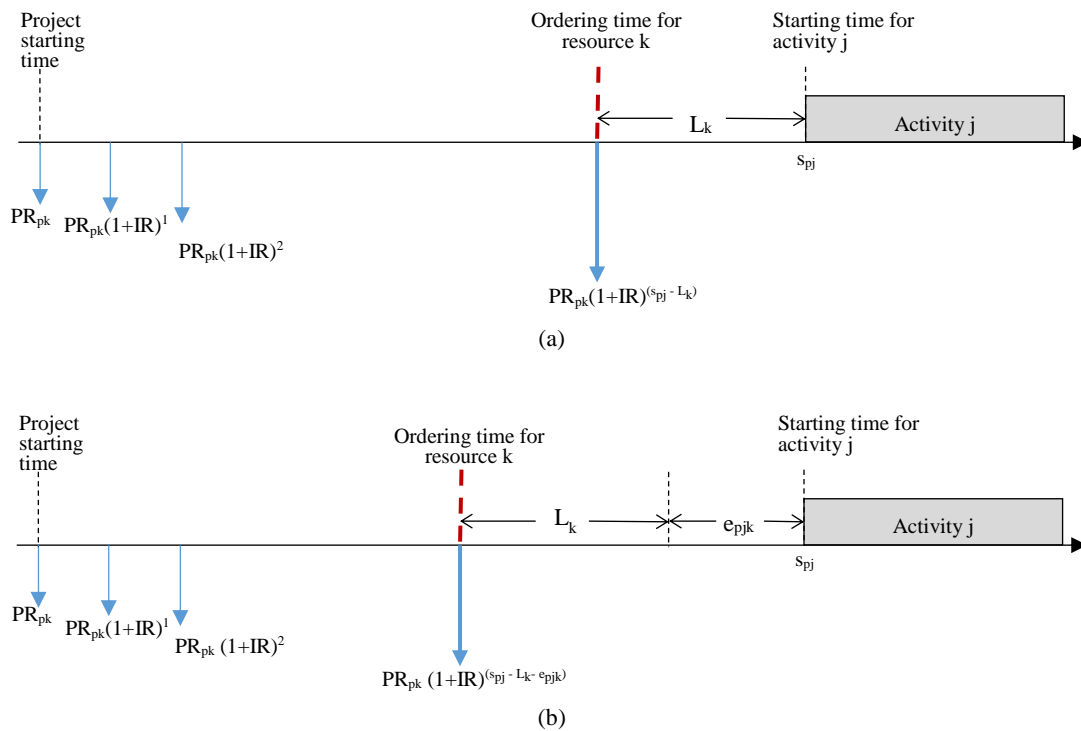


Figure 4. Purchasing savings from earlier ordering time

An activity with non-zero float can be delayed or unreasonably preempted without delaying the starting time of the successor activity. The fourth part of Eq. (1) is applied to prevent such unreasonable preemptions and delays. This part has a lower scale than the first three parts of the objective function which are expressed in monetary units, by the way this part will force the activities to be finished as soon as possible.

Eq. (2) ensures that the in-progress periods for each activity is equal to its duration.

$$\sum_t x_{pit} = D_{pj} \quad \forall p, \forall j \in N_p \tag{2}$$

Eq. (3) applies precedence relationships.

$$c_{pi} \leq s_{pj} - 1 \quad \forall p, \forall (i, j)^p \in A \tag{3}$$

Eqs. (4)–(6) calculate the completion and starting time for each activity based on its in-progress periods.

$$c_{pj} \geq t \cdot x_{pjt} \quad \forall p, \forall j \in N_p, \forall t \quad (4)$$

$$s_{pj} \leq t \cdot x_{pjt} + M(1 - x_{pjt}) \quad \forall p, \forall j \in N_p, \forall t \quad (5)$$

$$s_{pj} \geq t \left( 2x_{pjt} + \sum_{t'=t+1}^T x_{pjt'} - D_{pj} \right) \quad \forall p, \forall j \in N_p, \forall t \quad (6)$$

In order to clarify the above equations, an example with preemption is shown in Figure 5.

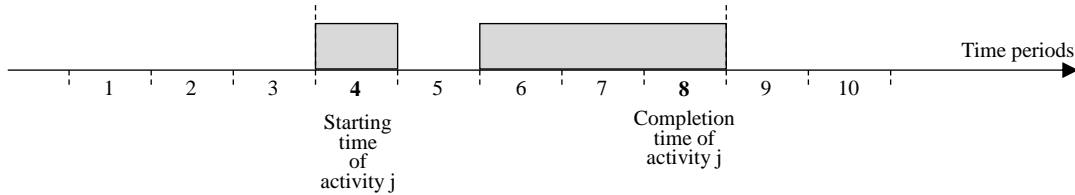


Figure 5. Calculation of the starting and completion times based on in-progress periods

In the example shown in Figure 5,  $x_{pj1} = 0$ ,  $x_{pj2} = 0$ ,  $x_{pj3} = 0$ ,  $x_{pj4} = 1$ ,  $x_{pj5} = 0$ ,  $x_{pj6} = 1$ ,  $x_{pj7} = 1$ ,  $x_{pj8} = 1$ ,  $x_{pj9} = 0$ , and  $x_{pj10} = 0$ . Hence, Eq. (4) allows  $c_{pj}$  to have the values 8, 9, 10 and above, but due to the fourth line of the objective function which should be minimized, it will take the value 8.

Eq. (5) allows  $s_{pj}$  to take the values 4, 3, 2, and 1. The right-hand side of Eq. (6) for different time periods will take the values 0, 0, 0, 4, -5, 0, -7, -16, -36, and -40. Hence, Eq. (6) allows  $s_{pj}$  to take the values 4, 5, ..., 10. The simultaneous application of Eqs. (5) and (6) allows  $s_{pj}$  to take on only the value 4.

Eq. (7) ensures that renewable resource assignments do not exceed their maximum available amount.

It is worth noting that nonrenewable resources have been considered unbounded. So, they appear only in the objective function.

$$\sum_p \sum_j R'_{pjk'} x_{pjt} \leq U_{k'} \quad \forall t, \forall k' \quad (7)$$

Eq. (8) ensures that each ordering time will be at least in the next period after completion of Activity 1, the design activity.

$$s_{pj} - e_{pjk} - L_k \geq c_{p1} + 1 \quad \forall p, \forall j > 1, \forall k \mid RR_{pjk} = 1 \quad (8)$$

Equation (9) limits  $e_{pjk}$  to its maximum available time interval. The maximum time interval for earlier ordering happens when sum of  $e_{pjk}$  and  $L_k$  is equal to the starting time of the related activity, as shown in Figure 3(b). When an activity does not need a resource,  $RR_{pjk} = 0$ , and this equation forces  $e_{pjk}$  to be zero.

$$e_{pjk} \leq RR_{pjk} (s_{pj} - L_k) \quad \forall p, \forall j, \forall k \quad (9)$$

Eq. (10) calculates the tardiness of each project, which will be minimized by the objective function.

$$td_p \geq c_{p,19} - Due_p \quad \forall p \quad (10)$$

Positive variables are declared in Eq. (11).

$$s_{pj}, c_{pj}, e_{pjk}, td_p \geq 0 \quad \forall p, \forall j, \forall k \mid RR_{pjk} = 1 \quad (11)$$

As mentioned above, the model is linearized by replacing Eq. (1) with Eq (1'). An innovative reformulation is developed for the inflation coefficients. A new parameter,  $V_t$ , is calculated for all time periods as  $(1 + IR)^t$ . Moreover, two new variables,  $y'_{pjk t}$  and  $y_{pjk t}$ , are defined and set out by Eqs. (12)–(15). Hence, the term  $(1 + IR)^{s_{pj} - L_k}$  is replaced with  $\sum_t y'_{pjk t} V_t$ , and similarly,  $(1 + IR)^{s_{pj} - L_k - e_{pjk}}$  is replaced with  $\sum_t y_{pjk t} V_t$ .

$$\begin{aligned} \text{Minimize } z = & \sum_p td_p CD_p \\ & + \sum_p \sum_j \sum_k H_k R_{pjk} e_{pjk} \\ & - \sum_p \sum_j \sum_k PR_{pk} R_{pjk} \left( \sum_t y'_{pjk t} V_t - \sum_t y_{pjk t} V_t \right) \end{aligned} \quad (1')$$

Eq. (12) ensures that only one period of time is determined for ordering a nonrenewable resource. If activity  $j$  of project  $p$  does not need resource  $k$ , all  $y_{pjk t}$  for this activity will be zero because  $RR_{pjk} = 0$ .

$$\sum_t y_{pjk t} = RR_{pjk} \quad \forall p, \forall j, \forall k \quad (12)$$

Eq. (13) detects the time period in which ordering takes place and forces the related  $y_{pjk t}$  to take the value 1.

$$\sum_t t \cdot y_{pjk t} = s_{pj} - L_k - e_{pjk} \quad \forall p, \forall j, \forall k \mid RR_{pjk} = 1 \quad (13)$$

Eq. (14) ensures that only one latest period of time is reported for ordering a nonrenewable resource. If activity  $j$  of project  $p$  does not need resource  $k$ , all  $y'_{pjk t}$  for this activity will be zero.

$$\sum_t y'_{pjk t} = RR_{pjk} \quad \forall p, \forall j, \forall k \quad (14)$$

Eq. (15) detects the latest possible ordering time for each purchase and forces the related  $y'_{pjk t}$  to be 1.

$$\sum_t t \cdot y'_{pjk t} = s_{pj} - L_k \quad \forall p, \forall j, \forall k \mid RR_{pjk} = 1 \quad (15)$$

#### 4. Numerical results

The proposed model was coded in GAMS 24.1.2 and solved using CPLEX solver on a server with a six-core 2.5 GHz CPU and 20 GB RAM. Computation time for large-sized real-world case was about 3 hours, which is reasonable for such a long-term problem.

First, two small-sized sample projects have been investigated in order to validate the results of the model and also to check the satisfaction all constraints. The sample projects include 5 activities shown in Figure 6 with different durations

and resource requirements. Two resources with 2 available units are defined. Projects 1 and 2 should be completed in 18<sup>th</sup> and 25<sup>th</sup> time periods, respectively. Other data is provided in Appendix.



Figure 6. Network of sample instance projects

Figure 7 illustrates the optimal schedule of all activities of two projects where P1 and P2 imply projects 1 and 2 and A1 to A5 show the activities of each project. As shown in the figure, project 1 will be completed with 1-day delay and project 2 will have 6-days delay. For project 1, no job is assigned to periods 3, 4, 8, and 9 because of material delivery lead times required for activities A2 and A3. Similarly, periods 4 and 5 are set empty for project 2. Common resource needed for activity 4 of project 1 (P1.A4) and activity 3 of project 2 (P2.A3) has resulted in a preemption in periods 12-14.

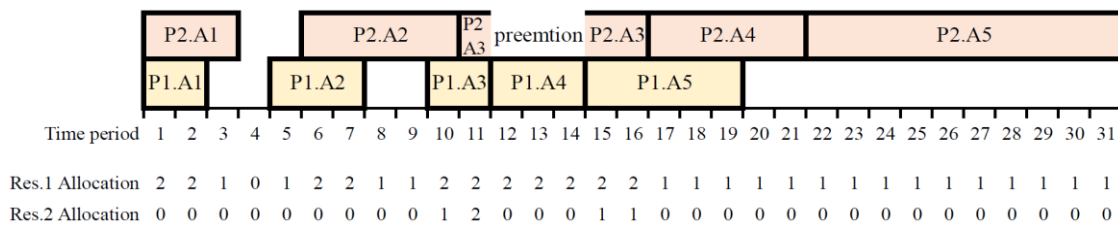


Figure 7. Sample project schedule

Optimal values of variable  $e_{pjk}$  are shown in Table 3. These values indicate the time intervals that a material is provided sooner than the time when it is required for starting the related activity. In order to check their rationality, a sensitivity analysis is conducted by altering the inventory costs. The results approved the rationality of the model where higher inventory costs resulted in lower  $e_{pjk}$  values, and vice versa.

Table 3. Optimal values for sooner purchasing

Project.Activity	Materials			
	M1	M2	M3	M4
P1.A3	0	4	0	0
P1.A4	0	0	5	0
P1.A5	0	0	0	7
P2.A3	0	4	0	0
P2.A4	0	0	9	0
P2.A5	0	0	0	13

After analyzing the small-sized samples, the real-world case with 10 projects of our case study has been investigated. The data of projects performed in a former year is gathered in order to compare the results of the model with current decisions made by the factory management. Because of confidentiality of financial data, the factory scaled all the monetary data, e.g., contract prices, raw material prices, and so on. Therefore, the monetary data is shown in this paper without currency unit. As mentioned before, 13 renewable and 63 nonrenewable resources are considered. Figure 8 illustrates the optimal schedule based on 18% inflation scenario.

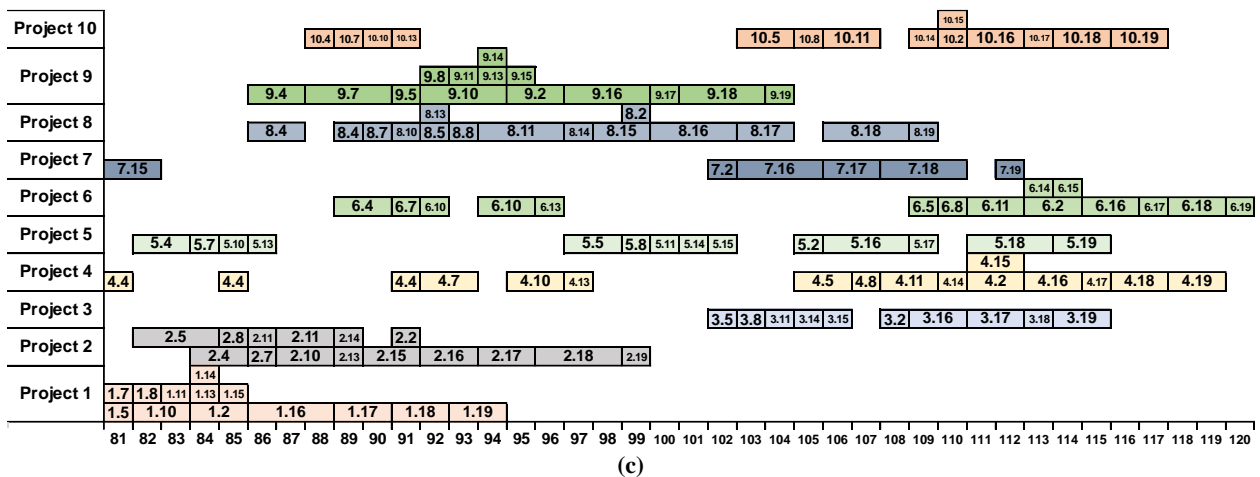
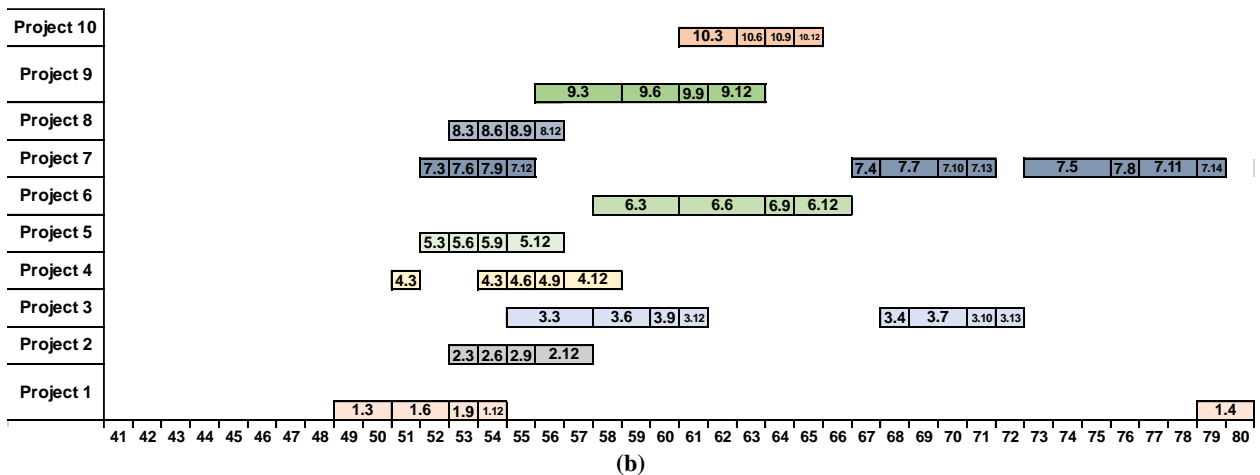
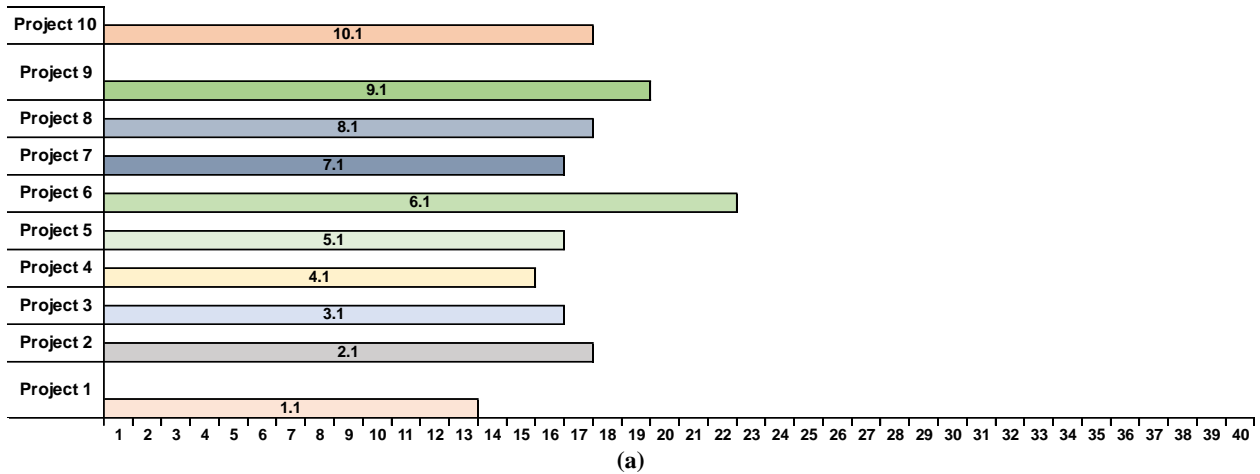


Figure 8. Graphical representation of optimal scheduling based on 18% inflation scenario

As shown in Figure 8, the time intervals between Activity 1 and the next activity in all projects are considerable, due to the long lead time of the purchased items. Some activities have been split based on renewable resource capacities. For example, as shown in Figure 8(b), Activity 3 of Project 4 needs a machine, of which the factory has one. At the same time, Activity 3 of both Projects 2 and 5 also need this machine. In this situation, the model has assigned the machine to Activities 4, 5, 2, and again 4. Similar preemptions are determined for several other activities.

The overall schedule pattern shown in Figure 8 has been verified by factory management via controlling precedence relationships, preemptions, capacity of renewable resources, floating times of activities, delays, and so on.

Compared to decisions made by management of the factory, a significant reduction in total delays is observed. Moreover, total costs are lessened by the trade-off done between the inventory and purchasing costs. Figures 9 and 10 demonstrate usefulness of our model in practice. These figures compare the total delays and total penalty costs due to the late completion of projects in the model solution against the real data from our case study. The proposed model gives an improvement of at least 50% in delays and 70% in delay penalties compared to the current status of the case study.

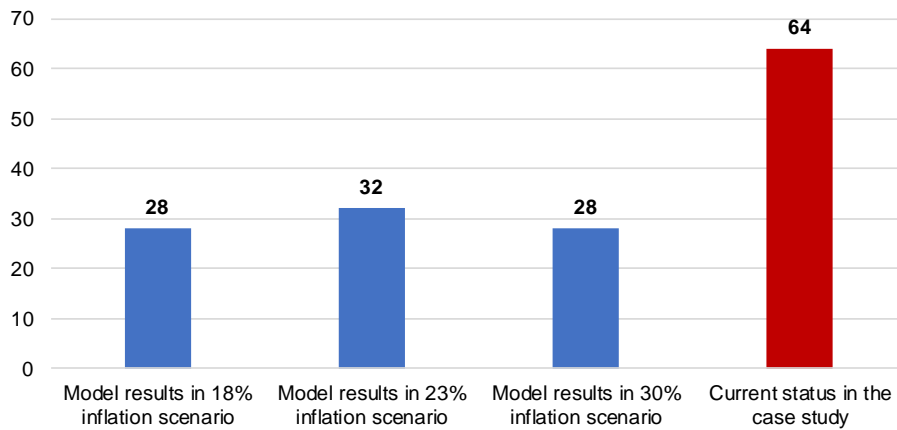


Figure 9. Total delays in model solutions compared to case study data

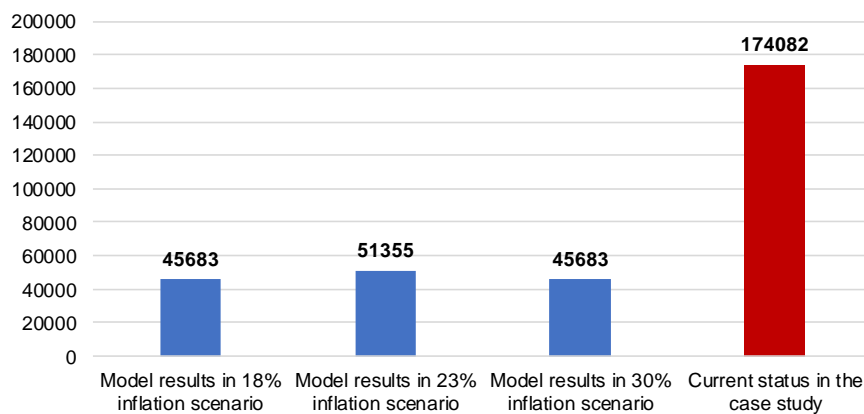


Figure 10. Total delay penalties in model solutions compared to case study data

Figure 11 shows the number of procurement items that are ordered earlier than their latest ordering time, for three inflation scenarios. As can be seen from the figure, an increase in inflation rate results in more and more items needing to be ordered sooner. This figure shows the logical behavior of the model for changes in the inflation rate. It worth noting that factory should be ready for more inventory volumes for higher inflation rates.

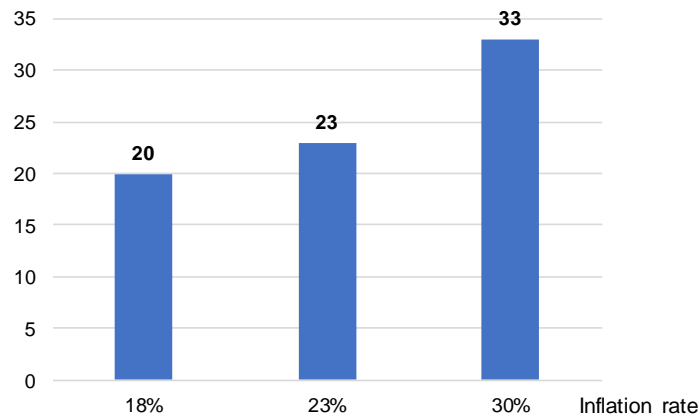


Figure 11. Number of procurement items ordered earlier than latest ordering time for three inflation scenarios

Figure 12 shows the total purchasing savings for three inflation scenarios.

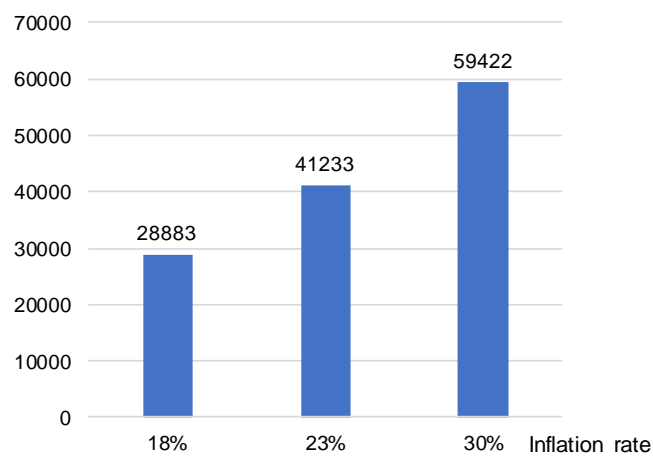


Figure 12. Total purchasing savings for three inflation scenarios

Similarly, the holding costs show logical behavior; here, an increase in the arrival-to-use period results in higher holding costs, as shown in Figure 13.

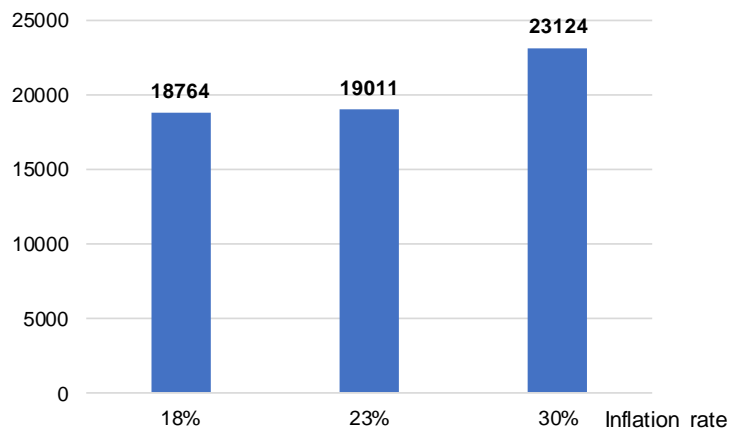


Figure 13. Total holding cost for three inflation scenarios

Figure 14 shows purchasing savings, delay penalties, and holding costs. As can be seen from this figure, purchasing savings significantly decrease the objective values in all inflation scenarios.

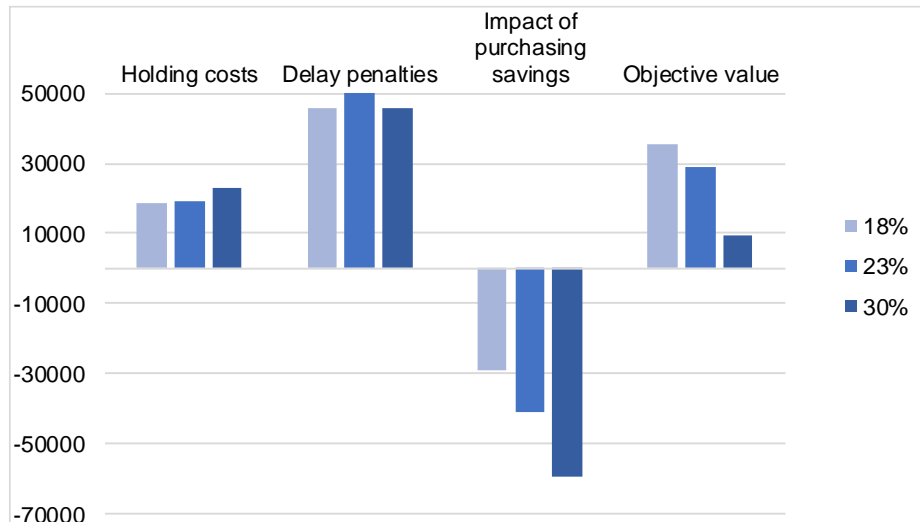


Figure 14. Objective value and its components for three inflation scenarios

As mentioned above, no prior research in this area has considered the effect of inflation on procurement decisions. In other words, problems have been optimized without considering inflation-related costs.

In order to show the impact of ignoring these costs, some modifications were applied to our model and results were compared. Eq. (1') was changed to Eq. (1''), and Eq. (16) was added to the model to calculate the deleted part of Eq. (1'). Variable  $z_z$  was added to  $z$  after solving the new model. The new model shows the sample behavior of relevant studies that do not consider inflation-related costs despite these having a significant impact on total costs, as shown in Figure 15. It can be seen from the figure that when purchasing savings are ignored, not only does this not help the objective function, but it also imposes significant costs on the system.

$$\begin{aligned}
 \text{Minimize } z &= \sum_p td_p CD_p \\
 &+ \sum_p \sum_j \sum_k H_k R_{pjk} e_{pjk}
 \end{aligned}
 \tag{1''}$$

$$z_z = -\sum_p \sum_j \sum_k PR_{pk} R_{pjk} \left( \sum_t y'_{pjk} V_t - \sum_t y_{pjk} V_t \right)
 \tag{16}$$

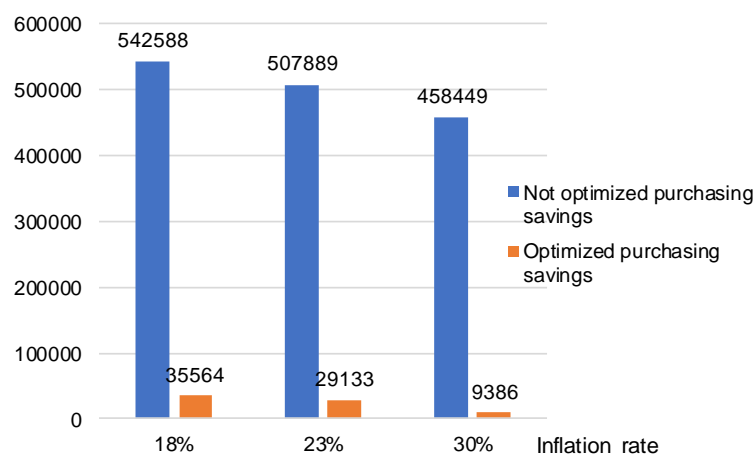


Figure 15. Objective value with and without consideration of inflation-based savings

## **5. Managerial insights**

Scheduling the activities of several projects is a complex problem that involves several considerations which cannot be optimized via try and error. The use of optimization models for this purpose can significantly improve total delays and their associated penalty costs.

Integrally consideration of project and procurement scheduling problems in MTO manufacturing environments is inevitable. Project scheduling helps to better manage operations and is an essential production managers' requirement. On the other hand, the schedule of the purchases should be in line with the schedule of activities in order to ensure that raw materials will be prepared at the right time that activities should be processed. On the other side, the optimal timing of purchases can change the schedule of activities. Therefore, these two integrated problems should be optimized simultaneously.

As the prices of raw materials change over time, especially in countries with high inflation rates, considering price inflations is vital. The results of this paper showed that the cost of purchasing raw materials has the greatest impact on the total costs and the optimal solution is significantly affected by this issue.

At higher inflation rates, the proposed model increases the number of raw materials that must be prepared earlier than the start of activity processing. Therefore, the factory must be ready to hold a higher amount of raw materials, as the inflation rate increases.

Even inventory costs will rise at high inflation rates, their increase is less than the purchasing cost savings.

Preempting some activities will allow the management to sequence them in empty time periods shorter than the activity durations. This can result in shorter total makespan and more productivity of resources.

Compared to the long-term horizon of planning, computation time of the proposed model is reasonable.

## **6. Conclusions**

A new mathematical model is proposed in this paper for a real case study of an MTO environment. The factory in the case study lacked a systematic approach to project and procurement scheduling. As a result, project delays and penalty costs were high, and customers were generally unsatisfied. The proposed model integrates project and procurement scheduling decisions with several real-world considerations, i.e., activity preemption, multiple project execution, and inflation rate, an important factor in the country studied. To the best of our knowledge, no existing research studies have considered inflation in this type of problem.

The main limitation of this research was confidentiality of financial data. Therefore, the factory scaled all the monetary data, e.g., contract prices, raw material prices, and so on. Consequently, the monetary data is shown without currency unit.

The results showed a significant improvement in total delays and consequently in the related delay penalties compared to the current status of our case study. The results also showed that inflation-related costs have a considerable impact on system costs, although these are ignored in the relevant literature.

In the judgment of experts, the proposed model showed logical behavior in terms of reasonable activity preemptions, early purchasing, holding costs, and overall schedule pattern.

Three scenarios were considered for the inflation rate, and the results show the following patterns:

- An increase in inflation rate increased the number of items purchased earlier;
- An increase in inflation rate increased the holding cost via a trade-off between holding costs and purchasing savings;
- The proposed model reduced the delay by 74%, 70%, and 74% in three inflation scenarios compared to the current status of the case study;
- The proposed model reduced the delay penalties by 56%, 50%, and 56% for the three inflation scenarios compared to the current status of the case study.

In summary, the key contributions of the proposed model can be summarized as follows:

- An integrated model is proposed for preemptive PSMO in a MTO production environment;
- Inflation is considered in project procurement scheduling;

- Multiple projects are considered, an aspect which is neglected in the relevant literature;
- The completion and starting times of activities are calculated in an innovative way based on in-progress periods;
- An innovative reformulation is proposed for the inflation coefficients.

There are several ways in which this research could be extended. Firstly, heuristic and/or metaheuristic approaches could be developed and compared to solve this problem for large-size instances. Another suggestion would be to consider possible uncertainties in model parameters. A consideration of the delivery risk and the incorporation of this in lead time calculations would also be interesting.

## References

- Alfieri, A., Tolio, T., Urgo, M., (2011). A project scheduling approach to production planning with feeding precedence relations. *International Journal of Production Research*, Vol. 49(4), pp. 995–1020.
- Alfieri, A., Tolio, T., Urgo, M., (2012a.) A two-stage stochastic programming project scheduling approach to production planning. *The International Journal of Advanced Manufacturing Technology*, Vol. 62(1-4), pp. 279–290.
- Alfieri, A., Tolio, T., Urgo, M., (2012b). A project scheduling approach to production and material requirement planning in Manufacturing-to-Order environments. *Journal of Intelligent Manufacturing*, Vol. 23(3), pp. 575–585.
- Alfieri, A., Urgo, M., (2015). Project scheduling for aggregate production scheduling in make-to-order environments. In: Schwindt C., Zimmermann J. (eds) *Handbook on Project Management and Scheduling*, Springer, Cham. pp. 1249–1266.
- Assaf, S., Hassanain, M.A., Abdallah, A., Sayed, A.M., Alshahrani, A., (2019). Significant causes of claims and disputes in construction projects in Saudi Arabia. *Built Environment Project and Asset Management*, Vol. 9(5), pp. 597–615.
- Budayan, C., (2019). Evaluation of delay causes for BOT projects based on perceptions of different stakeholders in Turkey. *Journal of Management in Engineering*, Vol. 35(1), pp. 1–13.
- Central bank of Iran, available at [https://www.cbi.ir/Inflation/Inflation\\_en.aspx](https://www.cbi.ir/Inflation/Inflation_en.aspx) (accessed 4 Dec 2019).
- Egri, P., Kovács, A., Markus, A., Vánca, J., (2004). Project-Oriented approach to production planning and scheduling in Make to Order Manufacturing. *Production Systems and Information Engineering*, Vol. 2(1), pp. 22–36.
- Fraz, A., Waris, A., Afzal, S., Jamil, M., Shah, S. T. H., Sultana, S., (2016). Effect of Project Management Practices on Project Success in Make-to-Order Manufacturing Organizations. *Indian Journal of Science and Technology*, Vol. 9(21), pp. 1–8.
- Goli, A., Alinaghian, M. (2020). A new mathematical model for production and delivery scheduling problem with common cycle in a supply chain with open-shop system. *International Journal of Manufacturing Technology and Management*, Vol. 34(2), pp. 174–187.
- Goli, A., Zare, H. K., Tavakkoli-Moghaddam, R., Sadeghieh, A. (2019). Application of robust optimization for a product portfolio problem using an invasive weed optimization algorithm. *Numerical Algebra, Control & Optimization*, Vol. 9(2), pp. 187–209.
- Goodier, C.I., Zhang, Y., Lord, W. E., Soetanto, R., (2018). Delay factors for international engineer-procure-construct (EPC) high-speed rail construction projects. *Conference and Annual General Meeting: A Productive Relationship: Balancing Fragmentation and Integration (ARCOM 2018)*, Belfast, UK, pp. 490–499.
- Habibi, F., Barzinpour, F., Sadjadi, S.J., (2019). A mathematical model for project scheduling and material ordering problem with sustainability considerations: A case study in Iran. *Computers & Industrial Engineering* 128, 690–710.
- Kadry, M., Osman, H., Georgy, M., 2017. Causes of construction delays in countries with high geopolitical risks. *Journal of construction engineering and management*, Vol. 143(2), pp. 1–11.

- Manzini, M., Urgo, M., (2015). Makespan estimation of a production process affected by uncertainty: Application on MTO production of NC machine tools. *Journal of Manufacturing Systems*, Vol. 37, pp. 1–16.
- Márkus, A., Váncza, J., Kis, T., Kovács, A., (2003). Project scheduling approach to production planning. *CIRP Annals* Vol. 52(1), pp. 359–362.
- Sabbagh, V., Salehi, M., (2017). Modeling and solving resource constraints project scheduling problem and material ordering for buying or producing. *International Journal of Industrial Engineering & Production Research*, Vol. 28(2), pp. 317–329.
- Shahsavari, A., Abbasi, B., Zoraghi, N., (2015). Material ordering with discount policy integrated with a project scheduling problem. *IEEE international conference on industrial engineering and engineering management (IEEM)*, pp. 1223–1226.
- Sheikh-Sajadieh, M., Shadrokh, S., Hassanzadeh, F., (2009). Concurrent project scheduling and material planning: A genetic algorithm. *ScientiIranica Transaction E: Industrial Engineering*, Vol. 16(2), pp. 91–99.
- Suppramaniam, S.U., Ismail, S., Suppramaniam, S., (2018). Causes of delay in the construction phase of oil and gas projects in Malaysia. *International Journal of Engineering & Technology*, Vol. 7(2.29), pp. 203–209.
- Tabrizi, B.H., Ghaderi, S.F., (2015a). A bi-objective model to address simultaneous formulation of project scheduling and material ordering. *World Academy of Science, Engineering and Technology, International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering*, Vol. 9(11), pp. 1897–1900.
- Tabrizi, B.H., Ghaderi, S.F., (2015b). An integrated mixed-integer programming model to address concurrent project scheduling and material ordering. *World Academy of Science, Engineering and Technology, International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering*, Vol. 9(11), pp. 1888–1891.
- Tabrizi, B.H., Ghaderi, S.F., (2016). A robust bi-objective model for concurrent planning of project scheduling and material procurement. *Computers & Industrial Engineering*, Vol. 98, pp. 11–29.
- Tabrizi, B.H., (2018). Integrated planning of project scheduling and material procurement considering the environmental impacts. *Computers & Industrial Engineering*, Vol. 120, pp. 103–115.
- Wei, F., Du, B., Tian, S., Li, Q., (2018). Prediction of material procurement delays in delivery for multi-variety and small batch manufacturing. *Journal of Beijing University of Aeronautics and Astronautics*, Vol. 31(3), pp. 78–83.
- Zoraghi, N., Najafi, A.A., Niaki, S.T.A., (2015). Resource constrained project scheduling with material ordering: two hybridized meta-heuristic approaches. *International Journal of Engineering*, Vol. 28(6), pp. 896–902.
- Zoraghi, N., Shahsavari, A., Abbasi, B., Van Peteghem, V., (2017). Multi-mode resource constrained project scheduling problem with material ordering under bonus–penalty policies. *Top*, Vol. 25(1), pp. 49–79.

**Appendix.** Detailed data of small-sized instances

**Table 4. Material lead time and unit holding cost**

Material	Lead time	Unit holding cost
M1	2	0.056
M2	3	0.090
M3	4	0.075
M4	5	0.020

**Table 5. Activity durations and resource requirements**

Project.Activity	Duration	Material requirements				Renewable resource requirements	
		M1	M2	M3	M4	R1	R2
P1.A1	2	0	0	0	0	1	0
P1.A2	5	1	0	0	0	1	0
P1.A3	2	0	0.5	0	0	1	1
P1.A4	3	0	0	0.25	0	2	0
P1.A5	5	0	0	0	1	1	0
P2.A1	3	0	0	0	0	1	0
P2.A2	5	1.5	0	0	0	1	0
P2.A3	3	0	0.75	0	0	1	1
P2.A4	5	0	0	0.4	0	1	0
P2.A5	10	0	0	0	1	1	0

**Table 6. Project due date and delay penalty**

Project	Due date period	Unit delay penalty
P1	18	90
P2	25	95