Sustainable Multi-period Production with Core and Adjacent Product Portfolio

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Abstract. Manufacturing and service companies need to increase service level to ensure their survival. However, in recent years this is not the only problem with production systems, the environmental impact became a major concern for manufacturing and service companies alike. In this article, we jointly consider time, cost, and environmental impact for production planning. To achieve this goal, collaborative decision-making with three decision-makers (DMs) is assumed to adjust sustainability performance through choosing the most suitable production type and appropriate production day. Financial managers, industrial managers, and environmental managers are three decision-makers who collaborate to improve responsiveness, and to reduce total production cost, and CO_2 emissions sequentially. To this end, a mixed-integer multi-objective mathematical model is suggested; Ɛ-constraint is used to solve the model. With the proposed model, DMs can make decisions on which products are produced on which day in a way to have trade-off among indicators.

Keywords: Product portfolio · Collaboration · Linear programming · Responsiveness · CO_2 emissions · Sustainable production

1 Introduction and Related Works

Firms are increasingly extending their offering with a wide variety of products, which has led to a lot of competition in meeting customers' demands. This led to many changes in the firms' environment based on the changes of customers' demands. In an environment that is constantly changing, firms must be more responsive to disruptions and manage all external and internal threats [1, 2]. Responsiveness in supply chains is the ability to respond to changes as quickly as possible [3]. This definition shows that there is a close relation between agility and responsiveness [4, 5]. Actually, agility is the response rapidly to the changes (e.g. in customers' demands) to increase the responsiveness of the supply chain [5, 6]. Although responsiveness is one of the topics discussed in detail in the supply chain [5, 7–11], only few studies were concerned with production management [4, 12].

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A very important point in the production system is that some products may have a lower priority than other products. For example in the Covid-2019 era, the production of masks or alcohol was a priority for cosmetics companies and a specific day (period) for their production and delivery was allocated. While some other products had lower priority and their production depended on their cost-effectiveness. Generally, low priority products can be produced on different days (period window) if they are economical. In this case, the preference of the production system is to produce them on the right day and at the same time in a fast way.

Reducing cost is not the only challenges companies face. Given the nature of the production and manufacturing industry, it can greatly contribute to climate change by, e.g., emitting Greenhouse Gases (GHGs) [13]. Due to the increase in GHGs, authorities, and policymakers tightened the regulations on emissions production. Recently, the European Commission proposed the first European Climate law, aiming at achieving a climate-neutral Europe by 2050 [14]. The report asserts that one of the intermediary steps is to reduce GHG emissions by at least 55% by 2030 compared to 1990. This indeed translates to emissions targets at the country and company levels. The emergence of environmental concerns motivated researchers to focus on emissions produced in production system. Furthermore, a production system is sustainable if any interaction has an impact on the economic, social, and environment [15]. These interactions, which can be taken, done in the manufacturing system are among the popular topics of literature in the last years [16, 17]. Sustainability is a vital key for the survival of the manufacturing systems, which can cover economic, environment, and human factors at the same time [18]. Although these objectives are essential to include in the real production systems, there are not enough academic studies in this field [18].

Although in the literature of supply chain [19] examined the relationship among responsiveness, cost, risk, and agility, in production management there is not any study to include sustainability concept in terms of responsiveness. The aim of [18] was to investigate how different levels of flexibility and agility (as two important antecedents of supply chain responsiveness) lead to different levels of responsiveness. In the publication, on the one hand, environment dimension was not included and on the other hand, all demands must be satisfied.

Within the limit of the current study, we jointly consider time, cost, and environmental impact for production planning. To achieve this goal, collaborative decision-making with three decision-makers (DMs) is assumed to adjust sustainability performance through choosing the most suitable production type and appropriate production day. Financial managers, industrial managers, and environmental managers are three decision-makers who collaborate to improve responsiveness, and to reduce total production cost, and CO_2 emissions sequentially.

A mixed integer multi-objective mathematical model is proposed to model the collaborative decision making problem and Ɛ-constraint is an approach to solve it. With the proposed model, DMs can make decisions on which products are produced on which day in a way to have trade-off among indicators.

The reminder of the article is organized as follows. Section 2 reports on the problem definition and presents the mathematical model. Section 3 presents the results of mathematical model for a small size problem to observe the value of indicators and illustrate decision making between DMs. Conclusion and future research propositions are summarized in Sect. 4.

2 Problem Description and Research Mode

Making a decision via collaboration of three DMs to determine the most efficient production plans in the appropriate period is the base of the current research. To achieve minimum costs and minimum CO_2 emissions beside maximization of responsiveness, three decision makers (financial manager, industrial manager, and environmental manager) collaborate to produce the most appropriate products. To determine optimal solutions, mathematical modelling was identified as the most appropriate approach. Mathematical models help DMs observe the effects their decisions on KPIs through multi-objective functions. A mixed integer mathematical programming model is proposed to produce two types of products in appropriate periods (the output of the model) to satisfy minimization of costs, saving CO_2 emissions, and maximization of responsiveness. The suggested model is a mixed-integer mathematical model involving binary variables (y_{it}) and integer variables (q_{it}). The two categories of products for which plans are generated are:

1. *Core products*: all the products in this category should be produced in a pre-defined period. Furthermore, if a product is set in this category, it is obligatory to be produced.
2. *Adjacent products*: products in this category are produced if they are appropriate to production (in terms of three indicators and collaboration of decision makers). These products are not compulsory and they can be produced at more than one specific period (period window). If a product is appropriate for production, it is produced in a most suitable and earliest period (to improve responsiveness).

The parameters and decision variables for the proposed model are described respectively in Tables 1 and 2.

The proposed mixed integer mathematical model is:

$$Min \sum_{i \in I} \sum_{t \in H} p\, c_{it} y_{it} \tag{1}$$

$$Min \sum_{i \in I_2} \sum_{t \in [\alpha_i, \beta_i]} y'_{it} \tag{2}$$

$$Min \sum_{i \in I} \sum_{t \in H} g\, \Theta_{it} \tag{3}$$

$st:$

$$\sum_{t \in [\alpha_i, \beta_i]} y_{it} \leq 1, \quad \forall i \in I_2 \tag{4}$$

Table 1. Parameters for the presented model

Symbols	Description
$I = I_1^h \cup I_2$	Set of total products variants (products in category 1 and products in category 2)
I_1^h	Set of products type 1 in period (day)h ∈ H
H	Time horizon
py	Production capacity
pc_{it}	Production cost of variant i ∈ I in period t ∈ H
g	Emissions produced (g) by a production of a variant i ∈ I
D_{it}	Upper demand limit for variant i ∈ I in period t ∈ H
d_{it}	Lower demand limit for variant i ∈ I in period t ∈ H
α_i	Lower bound of period window for product i ∈ I_2 in second category
β_i	Upper bound of period window for product i ∈ I_2 in second category
M	Big-M

Table 2. Decision variables of the proposed model

Symbols	Description
y_{it}	1, if and only if variant i ∈ I in period t ∈ H is produced; 0, otherwise
q_{it}	Representing production volume of variant i ∈ I in period t ∈ H
y'_{it}	Auxiliary variable (in the making linear of second objective function is used)
Θ_{it}	Auxiliary variable (in the making linear of third objective function is used)

$$y'_{it} \geq t \times y_{it} - \alpha_i, \quad \forall i \in I_2,\ \forall t \in [\alpha_i, \beta_i] \tag{5}$$

$$\sum_{i \in I} q_{it} \leq \sum_{i \in I} y_{it} py, \forall t \in H \tag{6}$$

$$d_{it} \leq q_{it} \leq D_{it}, \quad \forall i \in I,\ \forall t \in H \tag{7}$$

$$\Theta_{it} \leq M y_{it},\ \forall i \in I,\ \forall t \in H \tag{8}$$

$$\Theta_{it} \leq q_{it},\ \forall i \in I,\ \forall t \in H \tag{9}$$

$$\Theta_{it} \geq q_{it} - (1 - y_{it})M,\ \ \forall i \in I,\ \ \forall t \in H \tag{10}$$

$$\Theta_{it} \geq 0,\ \forall i \in I, \forall t \in H \tag{11}$$

$$y'_{it} \geq 0,\ \forall i \in I_2,\ \forall t \in [\alpha_i, \beta_i] \tag{12}$$

$$q_{it} \geq 0,\ \forall i \in I,\ \forall t \in H \tag{13}$$

$$y_{it} = 0\, for\, any\, i \in I_2\ and\ for\, any\, t \notin [\alpha_i, \beta_i] \tag{14}$$

$$y_{it} = 0\, for\, any\ i \in, I_1^h,\ t \neq h \tag{15}$$

First objective function minimizes total production costs (Eq. 1). Second objective function with Eqs. (5) maximizes responsiveness by minimization the difference between the lower bound (or the earlier possible production period) and the actual production period. Minimization of CO_2 emissions is indicated by third objective function (Eq. 3). Equations (4) ensures that an adjacent product can be either produced in a period within its period window or not produced. Constraints (6) and (7) check the maximum capacity of productions and demands. Constraints (8)–(10) are used to make linear the third objective function. Constraints (11)–(15) guarantee integrality and non-negativity condition for the decision variables.

3 Experimental Results

We solved the suggested mixed-integer linear programming model by Ɛ-constraint approach due to its easy application for enterprises where there are small size instances.

In the applied small instance, the time horizon covers 5 periods (days), the period window for products in second category is generated randomly between (1, 5). The rest of data like demands, maximum capacity, and CO_2 emissions are generated randomly or adopted from [20]. GAMS 12.6 implemented the Ɛ-constraint approach and the results are illustrated by Fig. 1 and Fig. 2. According to Fig. 1, different trade-offs between responsiveness and cost can be identified which facilitates negotiation and decision making between industrial and financial managers. In Fig. 2, the correlation between cost and CO2 emissions was depicted to observe what is the effects of increasing (decreasing) the costs on the environmental indicator. This figure is helpful for environment manager and financial manager to make decision about the environment and financial indicators by analysing the solutions on Pareto front. It is clear to save more CO_2 emissions; the enterprise has to spend more money. Generally, the proposed model is expected to be helpful for DMs to negotiate decisions on production plans based on different perspectives (financial, environmental, responsiveness).

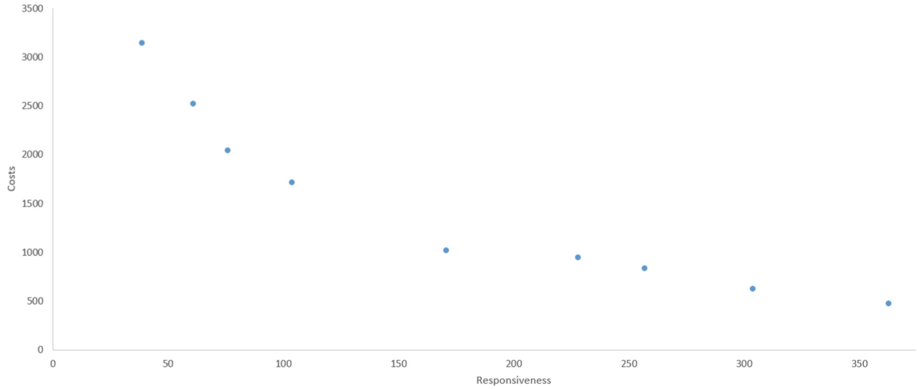

Fig. 1. Pareto front of first and second objective function (costs and responsiveness)

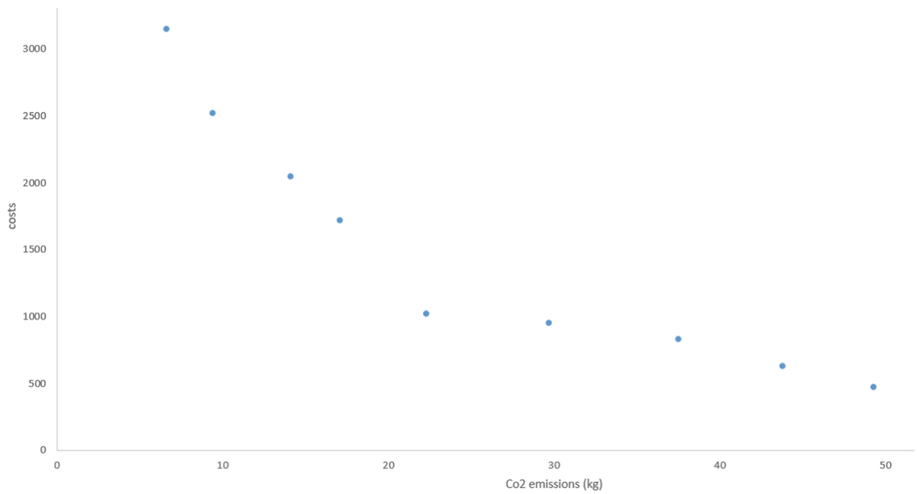

Fig. 2. Pareto front of first and third objective function (costs and CO_2 emissions)

4 Discussion and Conclusions

In this study, a mixed integer multi-objective mathematical model was suggested to produce two product categories in a time horizon. The objective is to minimize all the costs, increase responsiveness, and minimize CO_2 emissions. The problem was solved by Ɛ-constraint approach (for small size instances) to produce the most suitable combination of products in a time horizon.

This paper contribution is threefold: first, the model considers two category of products: high priority with predefined production day (core products) and low priority products with different days of productions (adjacent products). Second, the model focuses on three indicators covering some of the broad sustainability spectrum. Actually, by collaboration among three DMs (financial, industrial, and environment managers) the most suitable level in each indicator can be identified. Third, the model takes into account collaboration among decision makers. The model is expected to be useful for managing the ramp-up phase where newly developed products (adjacent) are progressively introduced into the market. This can benefit from the work of [20].

One limitation of the current research is the fact that risk is not considered in the model while it could be a key for companies to take planning decisions. Moreover, another perspective is to solve the presented model in large size instances with heuristics and metaheuristics algorithm. To this end, the challenge of data collection should be addressed. This task is complex because required data comes from multiple sources (environmental databases, cost data, etc.). Another challenge that shall be addressed is to include stochastic parameters to have a model more close to real applications.

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