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Capacity planning in textile and apparel supply chains

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This study deals with production and distribution planning for a textile and apparel supply chain. Given the seasonal nature of demand, global character of the textile and apparel supply chain, short life cycle of apparel products and demand unpredictability of trendy items, manufacturers require an efficient and flexible planning system that incorporates in-season replenishment orders with short lead time and preseason orders with medium lead time. A planning approach integrating tactical and operational decisions is proposed. Using a rolling horizon, the proposed approach determines the quantities to produce, store and deliver, which minimize the total production and distribution cost. At the tactical planning level, a percentage of production capacity is reserved in order to accommodate replenishment orders that are difficult to predict. Moreover, production of standardized items with predictable demand could be assigned to overseas low-cost subcontractors. For operational planning, local subcontracting and overtime could be used as options to address the unpredictability of the demand tied to replenishment orders. Our results show that the proposed approach results in a 10% cost saving over current practice.

Keywords: integer linear programming; production; distribution; flexibility; tactical and operational planning; textile and apparel industry.

1. Introduction

Currently, successful companies rely on the skills of supply chain management professionals to keep their goods and services flowing to markets quickly, efficiently and as cost-effectively as possible.

However, their success is currently challenged by a more complex supply chain structure involving several actors to provide the required product on time to the end consumer. Hence, any improvement in the supply chain performance requires planning, coordinating and managing production and distribution activities adequately to achieve an accurate and cost-effective order fulfilment including efficient shipments and on-time delivery of products. As shown in a literature review on integrated production and distribution models presented by Sarmiento & Nagi (1999), this trend leads to a closer link between the different stages of supply chain requiring better coordination in decision-making. For some applications involving perishable and/or seasonal products such as those of the fashion apparel industry, creating an intimate link between production and distribution decisions is even crucial to achieve the desired on-time delivery performance at minimum total cost (Chen, 2010).

This study focuses on the integration of production and distribution operations managed by a principal manufacturer of a global textile and apparel supply chain. A planning approach involving both tactical and operational decisions is proposed. This study is motivated by the inherent characteristics of the textile and apparel industry, which include the features of a global supply chain with multiple actors dispersed worldwide. Moreover, trendy apparel products are of wide variety and are characterized by a relatively short lifespan and unpredictable demand. Two types of orders are received: (1) preseason orders comprising items of the next selling season and characterized by a medium lead time and (2) replenishment orders comprising items of the current selling season and characterized by a relatively short lead time. In addition, textile and apparel manufacturers are facing a fierce global competition and an increasingly sophisticated consumer demand. As a result, the survival of textile and apparel companies depends on their quick response to changing and unpredictable demand according to consumer taste. In fact, inappropriate response leads either to lost sales on demands that cannot be met or to unsold inventory of items produced in excess of demand.

These characteristics are clearly pointed out in the works devoted to the study of textile and apparel industry (Choi *et al.*, 2018; Shen *et al.*, 2016; Margaret & Lucy, 2011; Pan *et al.*, 2009; Silva & Magalhaes, 2006; De Toni & Meneghetti, 2000; Karacapilidis & Pappis, 1996). However, it has been noted that only 3% of studies dealing with supply chain management investigated problems arising in this industry (Asgari *et al.*, 2016). In some of these studies (Choi *et al.*, 2018; Margaret & Lucy, 2011; Silva & Magalhaes, 2006; Karacapilidis & Pappis, 1996), even though they dealt with production activities only, it has been shown that the incurred planning problem is complex and challenging. Pan *et al.* (2009) investigated the ordering process of the apparel supply chain in order to minimize inventory and transportation costs; however, decisions related to production activities were not considered. Recently, Shen *et al.* (2016) conducted a literature review on research methodologies adopted for inventory management in the fashion industry. They concluded that inventory ownership, information technology and incentive schemes for increasing inventory efficiency are the key factors for enhancing inventory management in the fashion industry. For information technology, Choi *et al.* (2018) investigated the value of using Radio Frequency Identification (RFID) technology in the garment manufacturing supply chain. Based on empirical findings reported in the literature regarding lead-time reductions enabled by RFID technology deployment (Lee *et al.*, 2013; Kwok & Wu, 2009), the authors evaluated the resulting substantial increase in supply chain profit.

However, one of the most challenging issues is to jointly address the planning of production and distribution activities, which, to the best of our knowledge, has not yet been studied for the textile and apparel industry. The proposed approach considers the above-mentioned characteristics of this industry, mainly the need of the principal manufacturer to handle preseason and replenishment orders by wisely using a combination of flexibility potentials to overcome the inability of accurately forecasting replenishment orders before the start of product shelf life.

The remainder of this paper is organized as follows: Section 2 presents a literature review on integrated production–distribution planning. Section 3 describes the textile and apparel supply chain and the proposed production–distribution planning approach. Section 4 details the tactical and operational production–distribution planning models. In order to validate the proposed approach, experiments were conducted on an actual case study using data provided by the considered textile and apparel company. Section 5 is devoted to the presentation and discussion of the obtained results. Finally, in Section 6, concluding remarks and some avenues for future research are presented.

2. Literature review

The integrated production–distribution problem has received much attention from many researchers (e.g. Mula *et al.*, 2010; Erengüç *et al.*, 1999; Sarmiento & Nagi, 1999). In fact, as shown by Asgari *et al.* (2016), coordination is one of the supply chain management subject areas and production–distribution integration is one type of coordination. Most of the studies dealt with strategic and tactical planning levels (Chen, 2010). At the strategic level, decisions pertaining to capacity planning, network design and facility location are investigated (Kim *et al.*, 2007; Dias *et al.*, 2006; Vidal & Goetschalckx, 1997). However, the vast majority of published papers on integrated production–distribution planning dealt with the tactical level and investigated production, inventory, delivery lot size and assignment problems. From the literature, two types of models can be distinguished: single-level planning models and two-level planning models.

2.1 *Single-level planning models*

Various modelling and solution approaches have been proposed: Lee *et al.* (2002) and Lee & Kim (2002) developed a hybrid approach combining analytical and simulation methods, Aliev *et al.* (2007) and Selim *et al.* (2008) opted for fuzzy programming to incorporate uncertainty, Eskioglu *et al.* (2007) applied Lagrangian relaxation and decomposition techniques to solve this problem formulated as a multi-product flow problem and Armentano *et al.* (2011) proposed tabu search and path relinking heuristic solutions.

More recently, Lee (2015) examined production and transportation planning over a finite planning horizon. Two products can be produced in two different regions. The transportation in each period is constrained by a time-dependent capacity bound. A dynamic programming algorithm is used to solve optimally the considered planning problem.

Some studies dealt with supply chain planning (Zhong *et al.*, 2010; Boudia *et al.*, 2007) that emphasized production and distribution scheduling including product assignment to machines and vehicle routing decisions. To solve this operational planning problem, Zhong *et al.* (2010) devised a polynomial-time heuristic algorithm while Boudia *et al.* (2007) proposed an integer linear programming (ILP) model to simultaneously tackle production and routing decisions. To overcome the computational complexity of the proposed model, a greedy randomized adaptive search procedure solution approach was developed and then improved using a reactive mechanism and a path-relinking process. Kang *et al.* (2015) dealt with a semiconductor manufacturing case study, where outsourcing activity was considered while accounting for production, set-up and transportation costs. Genetic algorithm was used to find near-optimal solutions for the formulated mixed-integer linear program. Karaoglan & Kessen (2016) addressed production–distribution planning for perishable products with no inventory stage. They investigated the case of a single facility manufacturing a single product with limited shelf life; the transportation was performed using a single vehicle with limited capacity. The objective was to determine the minimum time required to produce and deliver the ordered products. To solve the problem, an approach using a branch-and-cut algorithm and a local search based on simulated annealing was proposed. Ngoc & Nananukul (2016) addressed an integrated production–distribution planning problem at the operational level involving a single production plant manufacturing different products to multiple customers. Bilgen & Celebi (2013) studied the production–distribution planning problem arising in multi-product dairy plants with consideration of product shelf life.

2.2 *Two-level planning models*

The aforementioned studies dealt with only one decision level. However, in another stream of research, two decision levels have been jointly tackled. In some studies, the authors developed one model encompassing the two decision levels (Bashiri *et al.*, 2012; Dhaenens Flipo, 2000; Fumero & Vercellis, 1997). In other studies, because of problem complexity, the authors opted for developing sequential multi-level planning approach, where a model is used for each decision level; coordination is ensured to guarantee the feasibility of the proposed solution and achieve the stated objectives (Das & Sengupta, 2009; Romo *et al.*, 2009; Sousa *et al.*, 2008; Özdamar & Yazgac, 1999).

Studies related to the integration of two decision levels are relatively abundant. However, most of the studies integrated strategic and either tactical or operational decision levels (Bidhandi *et al.*, 2009; Keskin & Üster *et al.*, 2007; Kim *et al.*, 2007; Tsiakis & Papageorgiou, 2007; Jayaraman & Pirkul, 2001; Sabri & Beamon, 2000; Cohen & Lee, 1988) and a few studies tackled tactical and operational decision levels (Khalili *et al.*, 2016; Romo *et al.*, 2009; Sousa *et al.*, 2008; Kanyalkar & Adil, 2005; Özdamar & Yazgac, 1999). Here, we will focus on works dealing with tactical and operational decision levels given that they are most relevant to our present study. Kanyalkar & Adil (2005) proposed an integrated multi-item, parallel multi-plant production and dynamic distribution problem. Infinite transportation capacity is considered without taking into account set-up and lead times. Romo *et al.* (2009) developed a single-period mixed-integer program to optimize the network configuration and routing for the main Norwegian shipper of natural gas. Khalili *et al.* (2016) addressed an integrated production–distribution planning problem considering risks related to operational supply chain disruption. A two-stage scenario-based mixed-integer stochastic programming model was developed. Özdamar & Yazgac (1999) proposed an iterative hierarchical planning approach to deal with production and transportation decisions. Two models were used: an aggregated model for tactical decisions and a disaggregated model detailing the tactical decisions into operational decisions. The developed models were based on the production system of a company manufacturing detergents. Distribution planning was limited to the transportation from the company's manufacturing units to its warehouses and did not include customer delivery. Sousa *et al.* (2008) addressed a multi-product and multi-period problem. A two-stage planning approach was proposed for an actual agrochemical supply chain. The first-stage model was developed considering a time horizon of 1 year. The second model was developed to deal with operational scheduling over a planning horizon of 1 month. The decisions made at the first stage are integrated into the second-stage model. It is worth noting that the operational planning model only accounts for internal production capacity and assumed that demand could not be fulfilled.

2.3 *Main contributions*

The discussion above shows the lack of studies that investigate integrated production–distribution planning in the apparel supply chain. As it can be observed, most of the studies investigated production–distribution planning of commodity products that have long life cycle and whose future demand can be accurately estimated. This is not the case for trendy apparel products whose life cycle is relatively short and related demand cannot be obviously predicted before the start of the season and putting the product on retail store's shelves. Moreover, it has been noted that the proposed models did not consider the possibility of resorting to flexibility options of production capacity such as overtime and subcontracting. However, given the unpredictability of demand and the importance of reducing production and distribution lead times in order to better adjust production to demand, these options should be considered in apparel supply chain planning. Therefore, it is necessary to devise production–distribution planning models and solution approaches that consider these important features of apparel supply chain. This study is devoted to start filling this gap.

Tactical and operational decisions are jointly considered in order to overcome demand unpredictability, ensure decision process consistency and achieve production–distribution planning objectives. Without integration, decisions made at the tactical level could lead to infeasible operational decisions or unexpected additional costs and, hence, suboptimal decisions. Moreover, integration of production and distribution planning is required to account for interactions between these two activities and achieve the optimal trade-off. Furthermore, the importance of integrating production and distribution decisions and planning decision levels has been clearly highlighted in the literature. For example, in a recent study on relief supply and network restoration required in post-disaster recovery operations, Ransikarbum & Mason (2016) promoted the use of integrated approaches. Moreover, they recommended the use of such approaches for complex production systems subject to disruptions and for studying production and distribution systems.

The main contributions of the present study can be summarized as follows:

– Devising a two-level integrated production–distribution planning approach that considers the most relevant features of apparel supply chain. The proposed approach incorporates tactical and operational decisions and considers both preseason and replenishment orders.

– Considering different flexibility options of production capacity in order to achieve a better match between supply and demand. At the tactical planning level, a percentage of production capacity is reserved for replenishment orders. This reserve production capacity offers some flexibility for fulfilling replenishment orders at the operational level. In addition, at the operational planning level, overtime and subcontracting options are used to overcome internal capacity shortage caused by demand peaks and reduced lead times of orders.

– Assessing the importance of considering a reserve production capacity and its effect on supply chain cost.

Finally, our aim is to propose a new planning approach that allows achieving a cost-effective and reliable production and distribution activities while taking into account the characteristics of trendy apparel products and the various constraints stemming from this industry.

3. Production–distribution planning approach

In this section, we present the manufacturing company involved in the supply chain described below (see Fig. 1) and the proposed production–distribution planning approach.

3.1 *Case study*

The studied company owns several manufacturing units and two warehouses, which are located in Tunisia. It also has the option of subcontracting some orders to local or overseas subcontractors. The

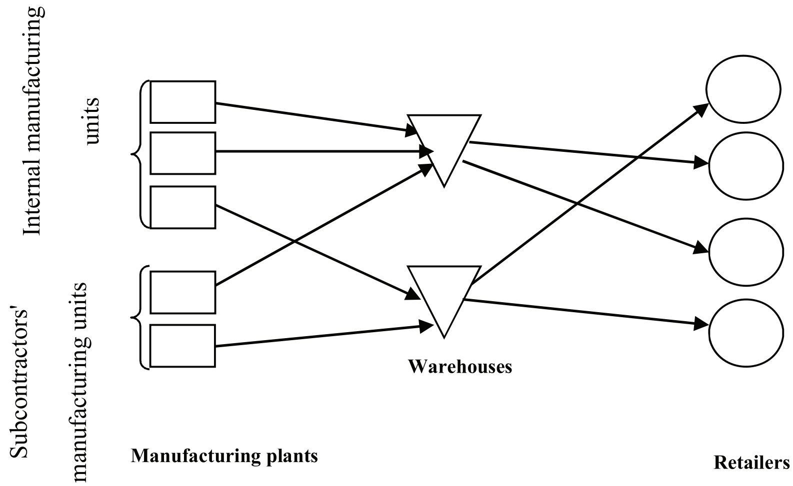

FIG. 1. The textile and apparel supply chain.

company is adopting a commit-to-delivery business model. It commits a delivery due date for any received order and is responsible for the shipping cost. The finished products are batched and shipped immediately to the warehouses where they are gathered and stored until their delivery time. Different transportation modes could be used for delivery operations: trucks, ships or aircraft. Each transportation mode is characterized by a fixed cost and variable cost. Each product incurs a production set-up cost and variable cost.

Orders received over one season contain a large number of product references. In general, the number of product families is greater than 100.

As mentioned above, the company receives two types of orders from local and overseas retailers: preseason and replenishment orders. Preseason orders with due dates of several months are predictable and planned ahead to meet the next season collections. However, replenishment orders with shorter due dates are generally difficult to predict and even urgent; they have to be produced to fill retailers' stock-outs or to replace unsold products. In fact, because of the short life cycles of textile and apparel products due to fashion changes, historical data alone cannot lead to accurate forecasts of future season sales (Mostard *et al.*, 2011). Moreover, prior to the start of the season, it is very difficult to predict the apparel items that would be required by consumers. That is why retailers usually resort to in-season replenishment opportunities after updating their forecasts based on the observed demand and trends over the first weeks of the current season.

3.2 *Planning approach description*

To address the unpredictability and short due dates of replenishment orders while meeting ongoing production, the company may, at the short run, resort to expensive options either by subcontracting production or by scheduling overtime. It is important to note that the subcontractors of the principal company are either local (providing flexibility in production capacity but at prices higher than internal production costs) or overseas subcontractors, having the capacity to provide large quantities of basic products at relatively low prices but with long delivery lead time. Obviously, only local subcontracting can be used for replenishment orders given their short delivery lead time.

Furthermore, in the tactical planning, only a given percentage of the production capacity is used. The rest of the capacity is actually referred to as reserve capacity and can be used only at the operational level to efficiently meet the demand with short due dates without disrupting the ongoing production. The objective is to satisfy retailers' preseason and replenishment orders on time, while minimizing the overall supply chain cost incurred by internal production, subcontracting, internal capacity underutilization, storage and distribution operations.

Product availability relying on in-season replenishment orders remains risky for the retailer as it hinges largely on the flexibility, reactivity and effectiveness of the involved suppliers. Hence, production flexibility to satisfy retailers' orders and ensure on-time deliveries becomes essential and a competing key issue for any textile and apparel manufacturing company.

Because the company is adopting a commit-to-delivery business model, it has to tackle the production and distribution planning problems jointly. The integrated approach for production and distribution planning, as shown in Fig. 2, is based on two mathematical models. The first model is developed to address the tactical planning problem. It considers a planning horizon of six 4-week periods taking into account the lead time of preseason orders. For simplicity, hereafter, each 4-week period is referred to as a month. The model considers received preseason orders and reserve production capacity and mainly decides on the quantity to produce internally and by third party manufacturers over each period of the planning horizon. A monthly rolling horizon is considered to integrate newly received preseason orders.

The second model is developed to solve the operational planning problem. It considers a variable planning horizon ranging from eight to eleven 1-week periods in order to properly detail production

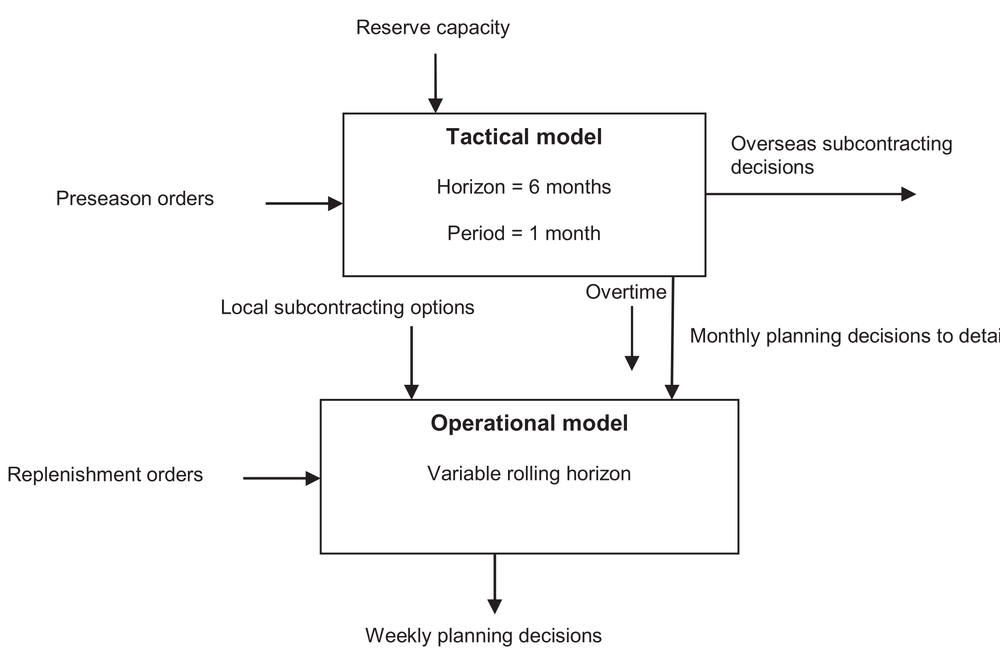

FIG. 2. Hierarchical planning approach.

decisions taken by the tactical model and hence strive to guarantee consistency between tactical and operational decisions. This choice will be explained further in Section 4.2.1. A weekly rolling horizon is considered to integrate newly received replenishment orders over weeks. It is worth noting that 8 weeks is the maximum lead time for a replenishment order. This also explains the length of the operational planning horizon.

The objectives of the operational planning model are twofold: (1) split the monthly planned quantities to produce internally, according to the tactical planning, over weeks and (2) introduce newly received replenishment orders over the weekly rolling horizon while recognizing their short lead time. The reserve production capacity considered at the tactical level is released and the entire internal capacity can be used in addition to overtime. This will provide more flexibility to accommodate unforeseen and urgent replenishment orders.

When a new preseason order with a delivery lead time larger than the number of periods of operational level arrives, it is introduced to the tactical planning model of the following month, to decide on production assignment while taking into consideration the capacity of subcontractors. The operational planning model could afterwards incorporate these orders if the tactical model proposes to produce them in internal manufacturing units. This procedure is repeated accordingly to the delivery lead times of orders.

Initially, in the operational planning model, the first 2 months are considered and the quantities to produce internally according to the tactical plan are broken down into quantities to produce over weeks. Quantities produced, stored and distributed at the first week are retained and related costs are recorded. However, decisions concerning the other periods (weeks) are released and reconsidered while running the operational planning model at the beginning of the following week, which allows incorporating the newly received replenishment orders. Finally, a weekly detailed production, storage and distribution plan is obtained. The latter incorporates the tactical production assignments and new replenishment orders.

The detailed tactical and operational planning models are introduced in Section 4.

4. Mathematical formulation

The following assumptions have been considered while developing the tactical and the operational planning models:

- Demand is assumed to be deterministic but dynamic over the planning periods,
- Inventory holding cost is calculated by considering the average inventory level between the beginning and the end of period,
- Underutilization capacity cost is estimated by means of hourly labour/machine cost.

4.1 *Tactical planning model*

The tactical planning model aims at minimizing total production, inventory holding and distribution costs. The outcomes of the tactical planning model include the following: monthly production quantities in internal and subcontractors' manufacturing units, monthly stored quantities in warehouses and monthly delivered quantities to retailers. Different transportation modes and production–distribution lead times are taken into account.

In model formulation, we consider the following sets and indices, parameters and decision variables.

Sets and indices:

$\mathcal{K}$: set of manufacturing units $k \in \mathcal{K}$; $K = \mathcal{U} \cup \mathcal{V}$

$\mathcal{U}$: set of internal manufacturing units, $k \in \mathcal{U}$

$\mathcal{V}$: set of subcontractors' manufacturing units, $k \in \mathcal{V}$

I: set of retailers, $i \in I$

$\mathcal{J}$: set of warehouses, $j \in \mathcal{J}$

$\mathcal{P}$: set of products, $p \in \mathcal{P}$

$\mathcal{L}$: set of transportation modes, $\mathcal{L} = \{\text{trucks, ships, aircraft}\}$, $l \in \mathcal{L}$

$\mathcal{T}$: set of periods included in the planning horizon, $t \in [1 .. |\mathcal{T}|]$

Parameters:

In this tactical model, each retailer i expresses a demand for product p to be delivered at period t ($\mathcal{D}_{pit}$). Orders are assigned to manufacturing units characterized by a monthly limited production capacity ($\mathcal{U}_{kt}$) where production takes place, incurring variable and fixed monthly production costs ($\mathcal{C}_{pkt}$, $\mathcal{S}_{pkt}$) or monthly subcontracting costs ($\mathcal{G}_{pkt}$). A monthly underutilization cost of internal production capacity ($\mathcal{CSU}_{kt}$) is also considered to penalize the unused available resources. Each product is characterized by a production lead time ($\mathcal{T}p_p$) and a products' unit volume ($\mathcal{V}_p$). Manufactured quantities are then transported to warehouses where monthly inventory holding costs ($\mathcal{KP}_{pjt}$) are incurred. Warehouses' storage capacity ($\mathcal{W}_j$) is limited. Transportation modes are characterized by a limited transportation capacity ($\mathcal{C}ap_l$) and a transportation lead time (e_l). Variable and fixed distribution costs from manufacturing units to warehouses ($\mathcal{CT}_{kjplt}$, $\mathcal{CF}_{kjlt}$) and from warehouses to retailers ($\mathcal{CS}_{jiplt}$, $\mathcal{CFS}_{jilt}$) are also considered. We denote the percentage of internal production capacity that can be used to fulfill preseason orders by α_{kt} ($k \in U$). As it can be noted, (100 - α_{kt}) represents the percentage of internal capacity reserved to fulfil in-season replenishment orders. Obviously, for $k \in V$ (V is the set of subcontractors' manufacturing units), $\alpha_{kt} = 0$.

Decision variables:

$\mathcal{Z}1_{kjplt}$: transported quantity of product p from manufacturing unit k to warehouse j over period t via transportation mode l.

$\mathcal{Z}2_{jiplt}$: transported quantity of product p from warehouse j to retailer i over period t via transportation mode l.

$\mathcal{X}_{pkt}$: quantity of product p produced in manufacturing unit k over period t.

$\mathcal{SU}_{kt}$: unused production capacity at internal manufacturing unit k over period t.

$\mathcal{I}_{pjt}$: inventory level of product p in warehouse j at the end of period t.

$\mathcal{Y}_{pkt}$ = 1 if product p is produced in manufacturing unit k over period t; 0 otherwise.

$\mathcal{N}1_{kjlt}$: Number of times transportation mode l is used to ship products from manufacturing unit k to warehouse j over period t.

$\mathcal{N}2_{jilt}$: Number of times transportation mode l is used to ship products from warehouse j to retailer i over period t.

Model formulation (M1)

The tactical production–distribution planning model is formulated as an ILP that aims at minimizing the overall cost in the considered supply chain network.

$$\text{Min}\left(\sum_{t\in\mathcal{T}}\sum_{p\in\mathcal{P}}\sum_{k\in\mathcal{U}}\mathcal{C}_{pkt}\mathcal{X}_{pkt}+\sum_{t\in\mathcal{T}}\sum_{p\in\mathcal{P}}\sum_{k\in\mathcal{U}}\mathcal{S}_{pkt}\mathcal{Y}_{pkt}+\sum_{t\in\mathcal{T}}\sum_{p\in\mathcal{P}}\sum_{k\in\mathcal{V}}\mathcal{G}_{pkt}\mathcal{X}_{pkt}\right.$$
$$+\sum_{k\in\mathcal{U}}\sum_{t\in\mathcal{T}}\mathcal{CSU}_{kt}\mathcal{SU}_{kt}+\sum_{j\in\mathcal{J}}\sum_{t\in\mathcal{T}}\sum_{p\in\mathcal{P}}\mathcal{KP}_{pjt}(\mathcal{J}_{pjt-1}+\mathcal{J}_{pjt})/2$$
$$+\sum_{t\in\mathcal{T}}\sum_{p\in\mathcal{P}}\sum_{k\in\mathcal{K}}\sum_{l\in\mathcal{L}}\sum_{j\in\mathcal{J}}\mathcal{CT}_{kjplt}{}^{*}\mathcal{V}_{p}{}^{*}\mathcal{Z}1_{kjplt}+\sum_{t\in\mathcal{T}}\sum_{p\in\mathcal{P}}\sum_{i\in\mathcal{I}}\sum_{l\in\mathcal{L}}\sum_{j\in\mathcal{J}}\mathcal{CS}_{jiplt}{}^{*}\mathcal{V}_{p}{}^{*}\mathcal{Z}2_{jiplt}$$
$$\left.+\sum_{t\in\mathcal{T}}\sum_{k\in\mathcal{K}}\sum_{l\in\mathcal{L}}\sum_{j\in\mathcal{J}}\mathcal{CF}_{kjlt}{}^{*}\mathcal{N}1_{kjlt}+\sum_{t\in\mathcal{T}}\sum_{i\in\mathcal{I}}\sum_{l\in\mathcal{L}}\sum_{j\in\mathcal{J}}\mathcal{CFS}_{jilt}{}^{*}\mathcal{N}2_{jilt}\right)$$

Subject to

$$\mathcal{J}_{pjt}=\mathcal{J}_{pjt-1}+\sum_{l\in\mathcal{L}}\sum_{k\in\mathcal{K}}\mathcal{Z}1_{kjplt-e_l}-\sum_{l\in\mathcal{L}}\sum_{i\in\mathcal{I}}\mathcal{Z}2_{jiplt}\qquad j\in\mathcal{J};p\in\mathcal{P};t\in\mathcal{T};t\geq e_l \tag{1.1}$$

$$\sum_{p\in\mathcal{P}}\mathcal{J}_{pjt}\leq\mathcal{W}_j\qquad j\in\mathcal{J};t\in\mathcal{T} \tag{1.2}$$

$$\sum_{p\in\mathcal{P}}\mathcal{T}p_p{}^{*}\mathcal{X}_{pkt}\leq\alpha_{kt}{}^{*}\mathcal{U}_{kt}\qquad k\in\mathcal{K};t\in\mathcal{T} \tag{1.3}$$

$$\mathcal{X}_{pkt}\leq\mathcal{M}^{*}\mathcal{Y}_{pkt}\qquad k\in\mathcal{K};p\in\mathcal{P};t\in\mathcal{T} \tag{1.4}$$

$$\mathcal{Y}_{pkt}\leq\mathcal{X}_{pkt}\qquad k\in\mathcal{V};p\in\mathcal{P};t\in\mathcal{T} \tag{1.5}$$

$$\mathcal{SU}_{kt}\geq\alpha_{kt}{}^{*}\mathcal{U}_{kt}-\sum_{p\in\mathcal{P}}\mathcal{T}p_p{}^{*}\mathcal{X}_{pkt}\qquad k\in\mathcal{U};t\in\mathcal{T} \tag{1.6}$$

$$\mathcal{X}_{pkt}=\sum_{j\in\mathcal{J}}\sum_{l\in\mathcal{L}}\mathcal{Z}1_{kjplt}\qquad k\in\mathcal{K};p\in\mathcal{P};t\in\mathcal{T} \tag{1.7}$$

$$\mathcal{D}_{pit}=\sum_{j\in\mathcal{J}}\sum_{l\in\mathcal{L}}\mathcal{Z}2_{jiplt-e_l}\qquad i\in\mathcal{I};p\in\mathcal{P};t\in\mathcal{T};t\geq_{el} \tag{1.8}$$

$$\sum_{p}\mathcal{V}_p{}^{*}\mathcal{Z}2_{jiplt}\leq\mathcal{N}2_{jilt}{}^{*}Cap_l\qquad j\in\mathcal{J};i\in\mathcal{I};l\in\mathcal{L};t\in\mathcal{T} \tag{1.9}$$

$$\sum_{p}\mathcal{V}_p{}^{*}\mathcal{Z}1_{kjplt}\leq\mathcal{N}1_{kjlt}{}^{*}Cap_l\qquad j\in\mathcal{J};k\in\mathcal{K};l\in\mathcal{L};t\in\mathcal{T} \tag{1.10}$$

$$\mathcal{Y}_{pkt}\in\{0,1\}\qquad k\in\mathcal{K};p\in\mathcal{P};t\in\mathcal{T} \tag{1.11}$$

$$\mathcal{Z}1_{kjplt}\in\mathbb{N};\mathcal{Z}2_{jiplt}\in\mathbb{N};\mathcal{X}_{pkt}\in\mathbb{N};\mathcal{J}_{pjt}\in\mathbb{N};\mathcal{N}1_{kjlt}\in\mathbb{N};\mathcal{N}2_{jilt}\in\mathbb{N};\mathcal{SU}_{kt}\in\mathbb{N} \tag{1.12}$$
$$k\in\mathcal{K};j\in\mathcal{J};p\in\mathcal{P};t\in\mathcal{T};l\in\mathcal{L};i\in I$$

The objective function minimizes the tactical planning cost composed of variable production cost, set-up cost, subcontracting cost, internal capacity underutilization cost, inventory holding cost, variable transportation cost from manufacturing units to warehouses, variable transportation cost from warehouses to retailers, fixed transportation cost from manufacturing units to warehouses and, finally, fixed transportation cost from warehouses to retailers. The transportation cost is composed of a variable cost, depending on the transported quantity using a transportation mode and a fixed cost depending on the selected transportation mode; the latter is proportional to the number of trucks, aircraft or ships used.

Constraints (1.1) calculate the inventory level of product p in warehouse j at the end of period t. Constraints (1.2) guarantee that over each period the total stored quantity does not exceed the warehousing capacity. Constraints (1.3) state that the produced quantities consider available internal production capacities while recognizing production lead times and reserve production capacity. Constraints (1.4) and (1.5) ensure the relationship between binary and integer variables. Constraints (1.6) with the objective function define the underutilized internal production capacity. Constraints (1.7) guarantee that all produced quantities are transported to warehouses. Constraints (1.8) state that products transported from warehouses to retailers satisfy the demand with respect to delivery lead times. Constraints (1.9) and (1.10) guarantee that over each period the transported quantities do not exceed transportation capacities. Constraints (1.11) and (1.12) are the integrality constraints.

4.2 *Operational planning model*

4.2.1 *Operational planning horizon.* As mentioned above, initially, the operational planning model considers a planning horizon comprising eight 1-week periods as this represents the longest lead time of replenishment orders. However, the operational planning also accounts for preseason orders stemming from the tactical planning. Therefore, the rolling operational planning horizon should reach the end of the month in order to consider and properly refine the decisions taken at the tactical level. Hence, a variable operational planning horizon is used. The number of 1-week periods included in the planning horizon depends on the position of the *first period* (week) of this planning horizon in the *month*; hence, it varies from eight to eleven 1-week periods as shown in Fig. 3. For example, if the first week of the operational planning horizon is the second week of month $\ominus$, then the length of the operational

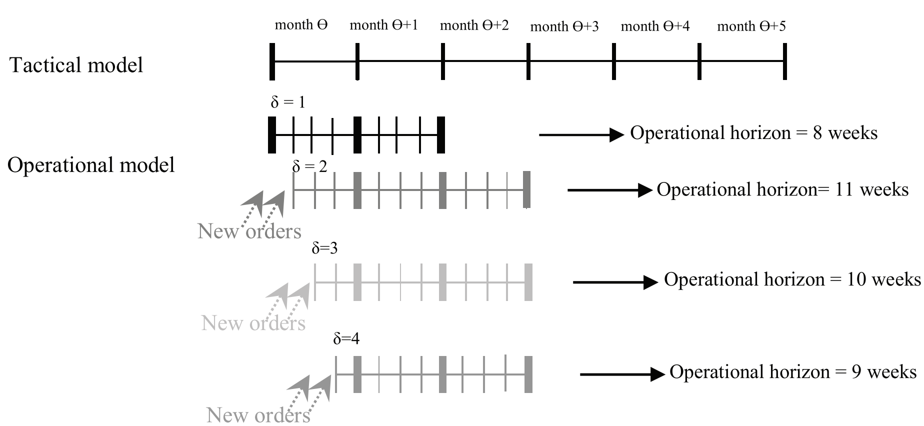

FIG. 3. Variable operational planning horizon

planning horizon will be set to 11 weeks because tactical decisions related to month $\ominus$+2 should be also considered.

Hereafter, each week in the operational planning model will be denoted by a couple (t, s), where s is the position of the week in month t.

Operational planning taking place at the beginning of week δ of month $\ominus$ includes a set of periods $\mathcal{TS}_{\ominus\delta}$ (see Table 1). For example, to construct an operational planning at the beginning of the second week ($\delta = 2$) of month $\ominus$, the periods involved are ($\ominus$,2), ($\ominus$,3), ($\ominus$,4), ($\ominus$+1,1), ($\ominus$+1,2), ($\ominus$+1,3), ($\ominus$+1,4), ($\ominus$+2,1), ($\ominus$+2,2), ($\ominus$+2,3) and ($\ominus$+2,4) and they are listed in the third column of Table 1 ($\mathcal{TS}_{\ominus 2}$).

TABLE 1. *Set of periods in the operational planning model used at week δ of month $\ominus$*

	$\delta = 1$	$\delta = 2$	$\delta = 3$	$\delta = 4$
(t, s) in $\mathcal{TS}_{\ominus\delta}$	($\ominus$,1) ($\ominus$,2) ($\ominus$,3) ($\ominus$,4) ($\ominus$+1,1) ($\ominus$+1,2) ($\ominus$+1,3) ($\ominus$+1,4)	($\ominus$,2) ($\ominus$,3) ($\ominus$,4) ($\ominus$+1,1) ($\ominus$+1,2) ($\ominus$+1,3) ($\ominus$+1,4) ($\ominus$+2,1) ($\ominus$+2,2) ($\ominus$+2,3) ($\ominus$+2,4)	($\ominus$,3) ($\ominus$,4) ($\ominus$+1,1) ($\ominus$+1,2) ($\ominus$+1,3) ($\ominus$+1,4) ($\ominus$+2,1) ($\ominus$+2,2) ($\ominus$+2,3) ($\ominus$+2,4)	($\ominus$,4) ($\ominus$+1.1) ($\ominus$+1,2) ($\ominus$+1,3) ($\ominus$+1,4) ($\ominus$+2,1) ($\ominus$+2,2) ($\ominus$+2,3) ($\ominus$+2,4)

4.2.2 *Model description.* The operational planning model employs the sets and parameters of the tactical model. Given that the tactical and operational models consider different periods, w has been added here to the parameters and the decision variables to indicate that they are related to a period of 1 week.

The operational planning model determines the quantities to produce, store and deliver over each week $(t, s) \in \mathcal{TS}_{\ominus\delta}$.

Recall that the production plans proposed by the tactical model for months t such as $(t,s) \in \mathcal{TS}_{\ominus\delta}$ are inputs to the operational model, as they have to be detailed per week.

The differences between the tactical and the operational model are summarized below:

– Only local subcontractors are considered in the operational model.

– Overtime could be planned to allow for a greater flexibility in handling the unpredictability and the short lead time of replenishment orders.

– Operational planning, in contrast to tactical planning, does not consider a reserve production capacity.

In addition to the notation introduced in the tactical planning model, we consider the following two parameters and two decision variables related to overtime:

Parameters:

$\mathcal{UH}w_{kts}$: overtime production capacity in internal manufacturing unit $k \in U$ at week s of month t with (t, s) in $\mathcal{TS}_{\ominus\delta}$

$\mathcal{CH}w_{pkts}$: overtime production cost of profuct p in internal manufacturing unit $k \in U$ at week s of month t with (t, s) in $\mathcal{TS}_{\ominus\delta}$

Decision variables

$\mathcal{XH}w_{pkts}$: quantity of product p produced during overtime in internal manufacturing unit $k \in U$ at week s of month t with (t, s) in $\mathcal{TS}_{\ominus\delta}$

$\mathcal{YH}w_{pkts}$= 1 if product p is produced during overtime in internal manufacturing unit k at week s of month t; 0 otherwise with (t, s) in $\mathcal{TS}_{\ominus\delta}$

Model formulation (M2)

The objective function minimizes operational planning costs. Similar to the objective function of the tactical model but considering weekly cost parameters and decisions, the first term represents the variable production cost and the second represents the set-up cost. The latter includes both the set-up cost for producing during regular working hours and during overtime. The third term is related to subcontracting and the fourth is related to production during overtime. The fifth term is the internal production capacity underutilization cost. The average inventory holding cost between successive weeks is represented by the sixth term. Finally, the last four terms are related to variable and fixed transportation costs from manufacturing units to warehouses and then from warehouses to retailers.

$$\begin{aligned}
\text{Min} \Bigg(& \sum_{(t,s)\in\mathcal{TS}_{\theta\delta}} \sum_{p\in\mathcal{P}} \sum_{k\in\mathcal{U}} \mathcal{C}w_{pkts}\mathcal{X}w_{pkts} + \sum_{(t,s)\in\mathcal{TS}_{\theta}\delta} \sum_{p\in\mathcal{P}} \sum_{k\in\mathcal{U}} \mathcal{S}w_{pkts}(\mathcal{Y}w_{pkts} + \mathcal{YH}w_{pkts}) \\
& + \sum_{(t,s)\in\mathcal{TS}_{\theta\delta}} \sum_{p\in\mathcal{P}} \sum_{k\in\mathcal{V}} \mathcal{G}w_{pkts}\mathcal{X}w_{pkts} + \sum_{(t,s)\in\mathcal{TS}_{\theta\delta}} \sum_{p\in\mathcal{P}} \sum_{k\in\mathcal{U}} \mathcal{CH}w_{pkts}\mathcal{XH}w_{pkts} \\
& + \sum_{(t,s)\in\mathcal{TS}_{\theta\delta}} \sum_{k\in\mathcal{U}} \mathcal{CSU}w_{kts}\mathcal{SU}w_{kts} + \sum_{j\in\mathcal{J}} \sum_{(t,s)\in\mathcal{TS}_{\theta\delta}} \sum_{p\in\mathcal{P}} \mathcal{KP}w_{pjts}(\mathcal{J}w_{pjts-1} + \mathcal{J}w_{pjts})/2 \\
& + \sum_{(t,s)\in\mathcal{TS}_{\theta\delta}} \sum_{p\in\mathcal{P}} \sum_{k\in\mathcal{K}} \sum_{l\in\mathcal{L}} \sum_{j\in\mathcal{J}} \mathcal{CT}w_{kjplts}\mathcal{V}_p\mathcal{Z}1w_{kjplts} + \sum_{(t,s)\in\mathcal{TS}_{\theta\delta}} \sum_{p\in\mathcal{P}} \sum_{i\in\mathcal{I}} \sum_{l\in\mathcal{L}} \sum_{j\in\mathcal{J}} \mathcal{CS}w_{jiplts}\mathcal{V}_p\mathcal{Z}2w_{jiplts} \\
& + \sum_{(t,s)\in\mathcal{TS}_{\theta\delta}} \sum_{l\in\mathcal{L}} \sum_{k\in\mathcal{K}} \sum_{j\in\mathcal{J}} \mathcal{CF}w_{kjlts}\mathcal{N}1w_{kjlts} + \sum_{(t,s)\in\mathcal{TS}_{\theta\delta}} \sum_{l\in\mathcal{L}} \sum_{i\in\mathcal{I}} \sum_{j\in\mathcal{J}} \mathcal{CFS}w_{jilts}\mathcal{N}2w_{jilts} \Bigg)
\end{aligned}$$

Constraints (1.1), (1.2) and (1.8)–(1.12) of the tactical model are also considered in the operational level while incorporating weekly parameters and decision variables. They enforce production flow balance, consideration of warehousing capacity, retailers' demand satisfaction and transportation capacity [(1.9) and (1.10)] and guarantee the integrality of decision variables [(1.11) and (1.12)].

Constraints (1.3)–(1.7) are replaced as follows in order to integrate overtime and full production capacity:

$$\sum_{p\in\mathcal{P}} \mathcal{T}p_p{}^{*}\mathcal{XH}w_{pkts} \leq \mathcal{UH}w_{kts} \qquad k \in \mathcal{U}; (t,s) \in \mathcal{TS}_{\ominus\delta} \tag{2.1}$$

$$\sum_{p\in\mathcal{P}} \mathcal{T}p_p{}^{*}\mathcal{X}w_{pkts} \leq \mathcal{U}w_{kts} \qquad k \in \mathcal{K}; (t,s) \in \mathcal{TS}_{\ominus\delta} \tag{2.2}$$

$$\mathcal{XH}w_{pkts} \leq M^{*}(\mathcal{YH}w_{pkts} + \mathcal{Y}w_{pkts}) \qquad k \in \mathcal{U}; p \in \mathcal{P}; (t,s) \in \mathcal{TS}_{\ominus\delta} \tag{2.3}$$

$$\mathcal{X}w_{pkts} \leq M^{*}(\mathcal{YH}w_{pkts} + \mathcal{Y}w_{pkts}) \qquad k \in \mathcal{K}; p \in \mathcal{P}; (t,s) \in \mathcal{TS}_{\ominus\delta} \tag{2.4}$$

$$\mathcal{YH}w_{pkts} + \mathcal{Y}w_{pkts} \leq 1 \qquad k \in \mathcal{U}; p \in \mathcal{P}; (t,s) \in \mathcal{TS}_{\ominus\delta} \tag{2.5}$$

$$\mathcal{YH}w_{pkts} \leq \mathcal{XH}w_{pkts} \qquad k \in \mathcal{U}; p \in \mathcal{P}; (t,s) \in \mathcal{TS}_{\ominus\delta} \tag{2.6}$$

$$\mathcal{Y}w_{pkts} \leq \mathcal{X}w_{pkts} \qquad k \in \mathcal{K}; p \in \mathcal{P}; (t,s) \in \mathcal{TS}_{\ominus\delta} \tag{2.7}$$

$$\mathcal{SU}w_{kts} \geq \mathcal{U}w_{kts} - \sum_{p\in\mathcal{P}} \mathcal{T}p_p{}^{*}\mathcal{X}w_{pkts} \qquad k \in \mathcal{U}; (t,s) \in \mathcal{TS}_{\ominus\delta} \tag{2.8}$$

$$\mathcal{XH}w_{pkts} + \mathcal{X}w_{pkts} = \sum_{l\in\mathcal{L}}\sum_{j\in\mathcal{J}} \mathcal{Z}1w_{kjplts} \qquad k \in \mathcal{K}; p \in \mathcal{P}; (t,s) \in \mathcal{TS}_{\ominus\delta} \tag{2.9}$$

Constraints (2.1) and (2.2) ensure the consideration of production capacity during both regular working time and overtime. Constraints (2.3), (2.5) and (2.6) ensure that overtime production cost is considered only in the case that there is no production of the same products previously. Constraints (2.4) and (2.7) ensure the relationship between binary and integer variables. Constraints (2.8) with the objective function define the underutilized internal production capacity. The distribution of all produced quantities to warehouses is enforced by constraints (2.9).

Constraints (2.10)–(2.14) are also added to the operational model:

$$\sum_{(t,s)\in\mathcal{TS}_{\theta\delta}/\delta\geq 1} \mathcal{X}w_{pkts} = \mathcal{X}_{pk\theta} - \sum_{s=1}^{\delta-1} \mathcal{X}w_{pk\theta s} \qquad k \in \mathcal{K}; p \in \mathcal{P}; t = \ominus \tag{2.10}$$

$$\sum_{(t,s)\in\mathcal{TS}_{\theta\delta}/\delta\geq 1} \mathcal{X}w_{pkts} = \mathcal{X}_{pk\theta+1} \qquad k \in \mathcal{K}; p \in \mathcal{P}; t = \ominus + 1 \tag{2.11}$$

$$\sum_{(t,s)\in\mathcal{TS}_{\theta\delta}/\delta\geq 1} \mathcal{X}w_{pkts} = \mathcal{X}_{pk\theta+2} \qquad k \in \mathcal{K}; p \in \mathcal{P}; t = \ominus + 2 \tag{2.12}$$

$$\mathcal{YH}w_{pkts} \in \{0,1\} \qquad k \in \mathcal{K}; p \in \mathcal{P}; (t,s) \in \mathcal{TS}_{\ominus\delta} \tag{2.13}$$

$$\mathcal{XH}w_{pkts} \in \mathbb{N} \qquad k \in \mathcal{K}; p \in \mathcal{P}; (t,s) \in \mathcal{TS}_{\ominus\delta} \tag{2.14}$$

Families of constraints (2.10), (2.11) and (2.12) ensure consistency with decisions made by the tactical planning model (M1). Finally, constraints (2.13) and (2.14) impose the integrality of the added decision variables.

5. Experimentation and results

5.1 *Experimental data*

The considered company has three knitting manufacturing plants located in Tunisia. Approximately 200 different knit product references are produced per year. Two warehouses located in Tunisia are used to store separately finished products ordered by local retailers and by overseas ones. Apparel items are then transported to retailers according to their delivery due dates. The company deals with approximately 30 retailers per year.

Transportation uses three modes: local deliveries are made by trucks, while ships or aircraft are employed for overseas shipping. When trucks are used, the incurred transportation cost is a fixed cost per delivery. The choice between ships and aircraft for overseas deliveries depends on committed lead times. Indeed, for ships, a period of approximately 5 weeks is required. However, delivery is made within the same week when air freight is used. Overseas transportation costs are composed of variable costs, depending on transported quantities, and fixed costs of freight, depending on the number of conveyance done in the same period.

The objective is to satisfy retailers' orders, which have to be delivered on time and at lower costs. In order to reinforce its production capacity and flexibility, the company works with 10 local subcontractors and 1 potential overseas subcontractor located in China. Working with subcontractors permits increasing the production capacity when it is necessary and thus provides flexibility. The Chinese subcontractor offers very competitive prices: a unit price for a basic product is almost half of its internal production cost. It has the capacity of producing large volumes of basic products but only orders having a lead time longer than 2 months can be assigned to it. Local subcontractors provide products with prices higher than internal production costs; on average, they are 20% higher than internal production costs. Production capacities of internal manufacturing units are limited. However, subcontractors' capacities are high enough to satisfy ordered quantities. For the 200 considered products, the internal production cost per unit ranges from €3 to €35.

The underutilization capacity cost is based on labour and machine hourly fixed costs. Internal manufacturing units can be used beyond regular working hours. Overtime is however limited to 25% of the production capacity over regular working hours and costs 40% higher. Finished products are gathered and stored in appropriate warehouses. These warehouses are characterized by their limited storage capacity and an inventory holding cost per unit of approximately 5% of unit production cost.

5.2 *Estimation of the reserve production capacity*

We propose to evaluate the impact of considering a reserve production capacity at the tactical planning level on the supply chain cost. In our experimentation, we are considering the same value for this reserve production capacity for all internal manufacturing units.

First, a fixed reserve production capacity is considered over each month of the tactical 6-month planning horizon. The percentage of internal production capacity available for preseason orders' planning is thus a fixed value denoted by alpha (α).

Second, we consider a reserve production capacity that varies from month to month. The percentage of internal production capacity considered in the tactical planning model is thus a monthly varying value denoted by (α_t), where t indexes the month.

The reserve production capacity has to be estimated a priori. Subsequently, we propose first to use available 2-year historical demand data to approximate the reserve production capacity ($1 - \alpha$ or $1 - \alpha_t$).

TABLE 2. *Observed internal production capacity rates used based on 2-year historical demand data*

Month →	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**Average**
Rate $_{\text{year}\,N-2}$(%)	62	90	89	71	61	76	75
Rate $_{\text{year}\,N-1}$(%)	75	91	72	91	87	95	85
Average rate	69	91	81	81	74	85	80

It is actually obtained by computing the ratio: replenishment production/total internal production during regular hours. The resulting internal production capacity rates are listed in Table 2.

5.3 *Numerical results and analyses*

We run the proposed approach over 6 months (M1, M2, M3, M4, M5 and M6) of year N, to obtain the production planning for each week and to determine storage details and distribution schedules.

In this experimentation, based on the newly received preseason and replenishment orders, the tactical planning model is run 48 times while the operational planning model is run 192 times.

All ILP models used by the proposed approach are solved using the package ILOG OPL Studio V6.3/ Cplex 11. The code is run on a PC Intel Core i5 with a 2.3-GHz processor and 512-MB memory. A near-optimal solution (with 10^{-4}gap from optimality) is obtained for all models run with no more than 5 min. For the tactical planning model, the number of constraints is approximately 122 000 and the number of variables is approximately 66 000 including more than 5000 binary variables. The operational model contains approximately 55 000 constraints and 25 000 variables including more than 3000 binary ones.

In order to assess the importance of considering a reserve production capacity at the tactical level, two types of production–distribution plans using the proposed approach have been investigated: (1) plans obtained without considering reserve production capacity and (2) plans obtained while considering reserve production capacity.

5.3.1 *Production–distribution planning without consideration of reserve production capacity.* This case represents the current textile and apparel production system of the principal manufacturer, as the latter does not consider any reserve production capacity in tactical planning. In this case, the supply chain cost obtained for the considered 6 months is equal to k€2864.

In the following, we test different values of reserve production capacity. The objective is twofold: (1) to show the importance of integrating a reserve production capacity in the tactical planning to gain flexibility and (2) to point out the necessity of developing adequate methods based on historical demand data that can provide accurate estimation of reserve production capacity.

5.3.2 *Production–distribution planning with fixed reserve production capacity.* We test different values of α ranging between 70% and 100% with a 5% gap between two successive values (see Table 3).

TABLE 3. *Supply chain cost as a function of* α

α	**70%**	**75%**	**80%**	**85%**	**90%**	**95%**	**100%**
Supply chain cost (k€)	3896	2990	2746	2667	2716	2723	2864

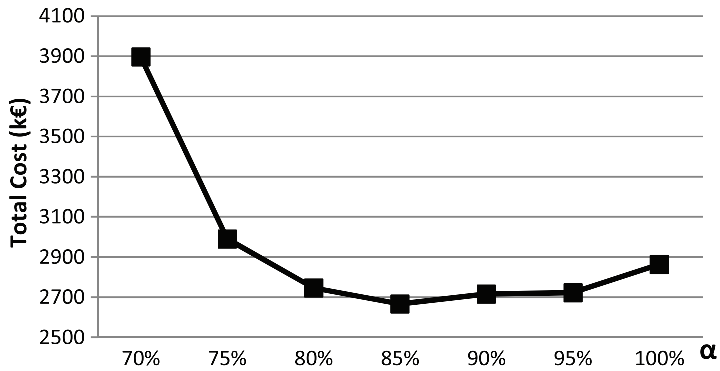

FIG. 4. Supply chain cost variation with α.

The choice of the range is based on the demand data-driven approximation of the reserve production capacity obtained as explained in the previous paragraph. For each value of α, the related supply chain cost is recorded as indicated in Table 3.

Fig. 4 shows the curve representing the variation of supply chain cost as a function of α. We can observe that the obtained curve has almost a convex shape. Higher costs are observed for 70, 75 and 100% α values.

Reserving 30–25% of the production capacity for replenishment orders leads to assigning many orders to subcontractors at the tactical level. Subsequently, a high capacity underutilization is observed at the operational planning level. When no reserve capacity is considered at the tactical planning (which is currently practised in the company), at the operational planning level, many replenishment orders are assigned to subcontractors or produced during overtime as internal production capacity is used during regular working hours to satisfy preseason orders.

We observe that in the actual case study considered, the optimum supply chain cost is obtained at an α value of approximately 85%. Therefore, a reserve production capacity of approximately 15% guarantees a production flexibility that minimizes the supply chain cost.

We also observe that $\alpha = 80\%$ is the average value obtained from the historical database (presented in Table 2). The corresponding supply chain cost is k€2746. As observed, this results in a 4% cost saving compared to the current practice ($\alpha = 100\%$). The cost saving over the current practice reaches 7% when the proposed planning approach is used with α equal to 85%, as indicated in Table 3.

5.3.3 *Production–distribution planning with monthly varying reserve production capacity.* In this part, we propose to test a monthly varying reserve production capacity. For each month t of year N, we consider the average of the percentage of internal production capacity used for years N- 1 and N- 2 as the value of α_t (presented in Table 2).

After introducing α_t values in the tactical planning model and applying sequentially tactical and operational models, we obtain a supply chain cost equal to k€2575. As observed, this supply chain cost is lower than the one obtained when a fixed reserve production capacity equal to 20% is considered. Hence, this reserve production capacity estimation method leads to a 6% cost reduction compared to the previous one. Moreover, it allows for a 10% cost saving over the current practice (Fig. 5).

This cost saving is due to the 6-month production assignment to internal manufacturing units and subcontractors shown in Fig. 6.

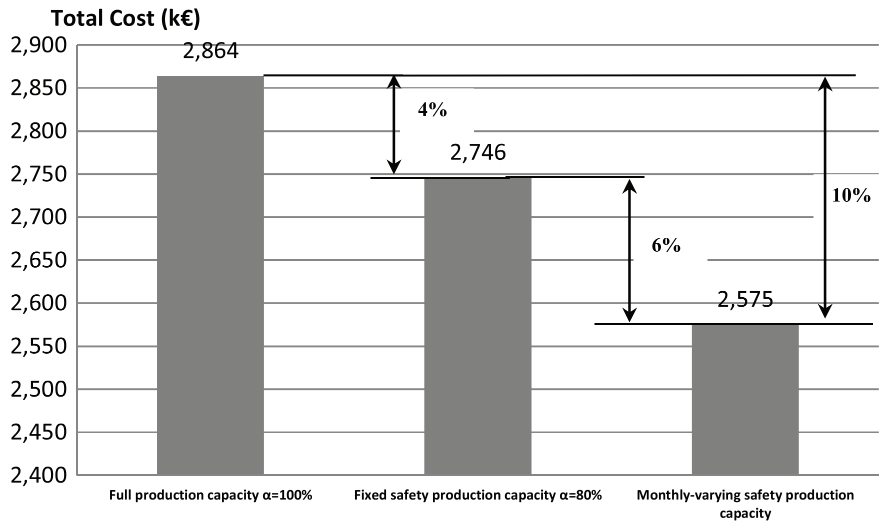

FIG. 5. Supply chain cost comparison.

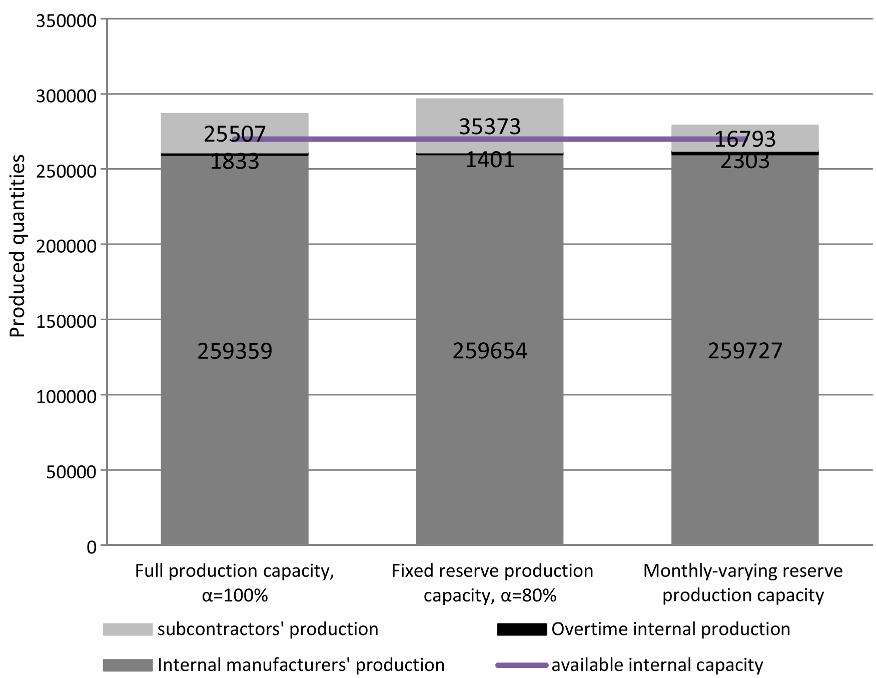

FIG. 6. Production assignment.

On one hand, we notice a better use of the internal production capacity when a monthly varying reserve production capacity is considered at the tactical level. On the other hand, we note that some production is performed during overtime, even though internal production capacity during regular hours is not fully utilized. This can be explained by the position of due dates of preseason orders over the month. Because production in internal manufacturing units over 1 month stemming from the tactical planning is detailed at the operational level per week, it is sometimes necessary to produce massively over the first weeks of the month in order to keep delivery due dates. Thus, overtime is used given that production during regular hours cannot satisfy the required quantities. Nevertheless, internal production capacity over the remaining weeks of the month could be underutilized.

At this point, it is worth noting that the produced quantities in subcontractors' manufacturing units, when a monthly varying reserve production capacity is considered, are less than those proposed when a fixed reserve production capacity is used (for both $\alpha = 80\%$ and $\alpha = 100\%$). Hence, production assignment to subcontractors is better optimized for monthly varying reserve production capacity. This result highlights the benefit of considering a monthly varying reserve production capacity adjusted to replenishment orders: production assignment to subcontractors is decided at the tactical level while adequately and accurately maintaining some internal production capacity to incorporate replenishment orders at the operational level.

Nevertheless, produced quantities in subcontractors' manufacturing units are particularly high when a fixed α, equal to 80%, is considered at the tactical level. At the same time, total quantities produced over the considered 6 months are larger than those produced when we consider α equal to 100%, or a monthly varying reserve production capacity. This is due to monthly demand variation. In fact, when a fixed reserve production capacity with α equal to 80% is considered, two situations could occur. First, replenishment orders to be satisfied during the month require more than the available capacity and thus require more than the reserve production capacity. In this case, production assignment to subcontractors is the main solution. In the second situation, replenishment orders to be satisfied during the month require less than the available capacity and thus require less than the reserve production capacity. Therefore, in order to minimize underutilization, replenishment orders to be satisfied for the next weeks are processed in advance. When a fixed α equal to 100% is considered, replenishment orders are assigned to subcontractors as full production capacity is used for preseason orders at the tactical level.

Finally, using a monthly varying reserve production capacity at the tactical level allows for an efficient use of internal production capacities and optimizes production assignment to subcontractors. However, the performance of capacity planning can be improved, if more accurate and reliable historical demand data are used and monthly varying reserve production capacity estimation methods are developed.

These numerical results ascertain the effect of considering a reserve production capacity on the supply chain cost by studying the three above-mentioned cases. In the next subsection, we discuss the sensitivity analysis carried out while considering the same three cases, in order to assess the effect of demand variation and subcontracting and transportation cost variation on the supply chain cost.

5.4 *Sensitivity analysis*

In the following, further analysis is conducted in order to investigate the impact of some parameters on planning decisions and the performance of the considered supply chain. Three parameters are examined: demand, transportation cost and subcontracting cost. Actually, these parameters could be subject to variation because of different factors such as competition, economic conditions and environment, changes in wage rates and fluctuating oil prices.

In our experimentation, 15 scenarios are considered while varying the (1) demand, (2) transportation cost and (3) subcontracting cost from -50 to +50%, around their current values. Similar to the previous experimentation, for each scenario, the supply chain cost is estimated while considering the same three cases: (1) no reserve production capacity is used ($\alpha = 100\%$), which reflects the current company practice, (2) a fixed reserve capacity is used at the tactical level with $\alpha = 80\%$, and (3) a monthly varying reserve production capacity is used.

5.4.1 *Sensitivity analysis of demand.* As observed from Table 4, an increase in demand from -50 to +50% leads to an increase in the supply chain cost. However, for the same demand, a reduction of this cost is recorded when a reserve production capacity is considered. In all demand scenarios, the highest cost saving is achieved when a monthly varying reserve production capacity is introduced in the tactical planning.

TABLE 4. *Cost variation according to demand*

	D-50%	**D-20%**	**D**	**D+20%**	**D+50%**
$\boldsymbol{\alpha = 100\%}$ **(k€)**	1658	2152	2864	3285	3794
$\boldsymbol{\alpha = 80\%}$ **(k€)**	1632	2020	2669	3067	3581
$\boldsymbol{\alpha}$ **variable (k€)**	1596	1981	2575	2972	3389

The results obtained confirm the great significance of our approach and promote the idea of using a reserve production capacity to reduce supply chain costs. Even in the case where the demand is reduced by half, consideration of a monthly varying reserve capacity yields a better performance: a cost saving of 4% is achieved compared to the current practice. This cost saving reaches 11% when the demand is increased by half. Thus, the use of the proposed approach is essential when the demand is relatively high. When the demand is low and could be satisfied using internal production capacities, at the tactical planning, the production load would not reach the ceiling of internal production capacity in general; hence, imposing a reserve production capacity becomes less important. In this latter case, considering a reserve production capacity helps to prevent undercapacity situations caused by urgent demand peaks.

5.4.2 *Sensitivity analysis of transportation and subcontracting cost.* The same trend appears subsequently to the variation in transportation and subcontracting costs. Again, cost saving is achieved when a reserve production capacity is considered at the tactical planning level (Fig. 7). Noticeably, the highest cost saving is achieved when a monthly varying reserve production capacity is considered. In addition, the cost saving becomes more significant with the increase in these two costs.

A decrease in transportation costs incurs the migration of some *internal productions* to the manufacturing unit of the overseas subcontractor because it offers very competitive prices particularly for basic products. Subsequently, at the tactical planning level, a part of the internal production capacity is left unutilized; hence, imposing a reserve production capacity becomes less important. This justifies why the lowest cost saving is observed when the transportation cost is reduced by half.

However, overseas subcontracting is no longer the recommended option when transportation cost increases. This encourages the use of a reserve production capacity to prevent the use of full

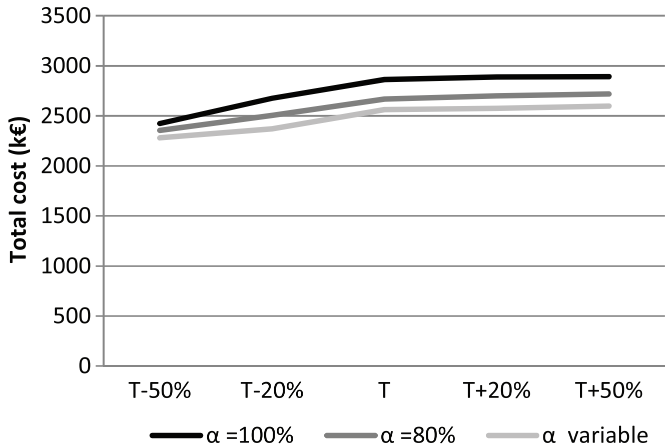

FIG. 7. Transportation cost variation.

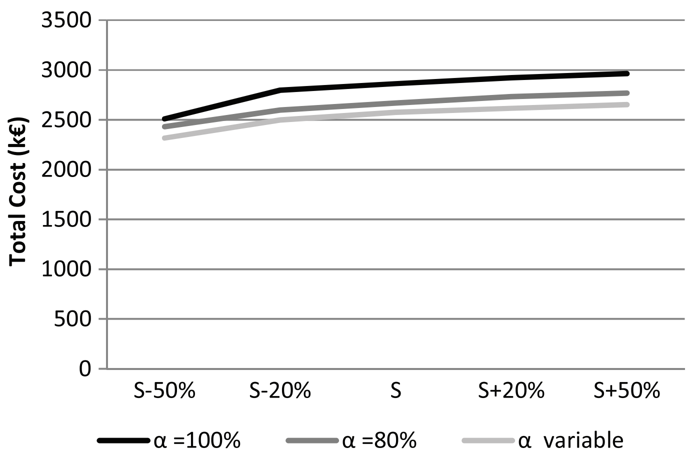

FIG. 8. Subcontracting cost variation.

production capacity at the tactical level. Internal production (over regular hours and overtime) and local subcontracting are the chosen options to handle capacity requirements.

Concerning the subcontracting cost, its reduction by half makes it more competitive than internal production. Thus, much of the internal production migrates to the manufacturing units of local subcontractors. The cost incurred by underutilization of internal production capacity prevents migration of the total quantities to local subcontractors' plants. Internal production capacities are underutilized but the situation induces a lower supply chain cost caused by the decrease in production costs. The consideration of a reserve production capacity becomes less important in this case.

However, an increase in supply chain cost is recorded when the subcontracting cost increases particularly for the current practice ($\alpha = 100\%$). Actually, subcontracting is avoided until the internal production capacity (during regular hours and overtime) is fully utilized; this situation leads to local subcontracting at higher costs (Fig. 8). In this situation, the consideration of a reserve production capacity seems substantial to guarantee the use of overseas subcontracting (incurring lower cost than local subcontracting) at the tactical level. When subcontracting cost is increased by half, the consideration of a monthly varying reserve production capacity permits reaching a cost saving of 11% compared to the current practice.

5.4.3 *Managerial insights.* The sensitivity analysis on demand, transportation and subcontracting costs confirms the aforementioned findings. Furthermore, it highlights the importance of considering a reserve production capacity when demand, transportation cost and subcontracting cost are relatively high.

In a broader scope, opting for the proposed approach is particularly recommended in supply chains where manufacturers have to handle predictable orders with long delivery lead time and hard-to-predict orders with relatively short delivery lead time. Being a supplier also, a manufacturer must be effective by responding promptly to the different types of orders from its customers. In the current business environment characterized by fierce competition, it is not enough for the manufacturer to focus on developing desirable products; it also needs to provide these products when required and offer them at reasonable prices. The adoption of a big picture approach integrating supply chain actors and developing an adequate planning policy that emphasizes flexibility and responsiveness to customer needs and wants is the key to achieve cost reduction and gain competitiveness.

Moreover, the supply chain performance can be improved if more reliable historical demand data are used and more sophisticated monthly reserve production capacity estimation methods are developed. That is why cooperation between the manufacturer and retailers based on information sharing should be encouraged. In addition to a better estimation of reserve production capacity considered at the tactical level, sharing of information on ongoing sales will allow the manufacturer to predict future replenishment orders with more accuracy and adjust production capacity at the operational level accordingly. The latter is one of the important prospects of this study.

6. Conclusion and further research

In this study, we propose a sequential approach integrating tactical and operational decisions for textile and apparel supply chain planning. The objective is to achieve cost minimization and customer satisfaction through responsiveness and on-time delivery.

For this industry, there is an urgent need to develop new planning approaches that take into account demand characteristics: unpredictability, fashion dependency and short life cycle. In this context, production and distribution planning are closely linked and have to be planned in such a way that flexibility of different schedules is maximized. The purpose is to emphasize flexibility. For this reason, a reserve production capacity is implemented at the tactical level to provide more flexibility at the operational level, so that weekly new replenishment orders with short due dates can be accommodated through the rolling horizon. The objective is to minimize the supply chain cost while ensuring on-time deliveries.

First, we evaluated the supply chain cost when the entire available production capacity is considered in the tactical planning. Second, we tested our approach with different values of reserve production capacity and we pointed out that the optimum supply chain cost could be obtained when approximately 15% of production capacity is not allowed at the tactical planning level. Third, considering historical demand data, we tested other values for reserve capacity: (1) a fixed value for all months and (2) monthly varying values. Finally, we observed that the consideration of monthly varying reserve production capacity at the tactical level led to a better placement of replenishment orders. A cost saving of 10% can be achieved over the current practice that does not consider a reserve capacity at the tactical level. This significant gain reflected the effectiveness of the approach developed to address unpredictable textile and apparel demands.

The proposed approach is tested using actual data from the considered company over a 6-month planning horizon. However, the approach can also be applied on a longer planning horizon. The main objective is to evaluate the proposed approach and to determine the cost saving that could be achieved if internal production capacity is adequately and efficiently planned.

For this present work, the producer had no advance information on current sales and therefore, no advance information on replenishment orders that could occur. However, for future work, we propose to consider a supply chain coordination through informational flows, where the retailers share the information they have on future replenishment orders of outlets with the producer. This advance information will allow the producer to anticipate and plan a reserve production capacity at the operational level. The latter will be adjusted over weeks, based on forecasts of future replenishment orders and considering a weekly variable adjustment rate. A comparison will then be established between the different approaches in order to study their performance on the textile and apparel supply chain costs and profitability. Moreover, the proposed planning models assume that the demand is deterministic. These models will be extended by assuming that the demand is stochastic. Therefore, stochastic programming models and appropriate solution approaches will be devised.

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