Modelling and Solving Spare Parts Supply Chain Network Design Problems

Francisco J. Tapia-Ubeda[a,b]*, Pablo A. Miranda[c], Irene Roda[b], Marco Macchi[b] and Orlando Durán[d]

[a]*School of Industrial Engineering, Pontificia Universidad Católica de Valparaíso, Valparaíso, Chile;* [b]*Department of Management, Economics and Industrial Engineering, Politecnico Di Milano, Milano, Italy;* [c]*Department of Engineering Sciences, Universidad Nacional Andres Bello, Viña del Mar, Chile;* [d]*School of Mechanical Engineering, Pontificia Universidad Católica de Valparaíso, Quilpúe, Chile.*

*Corresponding author. Email: franciscojavier.tapia@polimi.it

ABSTRACT

Spare parts are key operational assets in order to minimize the unexpected equipment downtimes that may significantly impact the company results. Accordingly, the spare parts supply chain network supports the entire spare parts operations and it is essential to achieve the planned goals. However, traditional literature on spare parts management has not focused on the underlying supply chain network. Thus, this paper studies the integration of supply chain network design and control with traditional spare parts management. In particular, this paper proposes a generic network optimization modelling structure, with simultaneous decisions for warehouse locations and inventory control, allowing to optimize the total costs of the spare parts supply chain network. The generic model is specified based on three inventory control policies widely used in industrial sites, i.e. (s, Q), (R, s, S) and (S-1, S), which are suitable for managing a great variety of spare parts. Furthermore, a decomposition-based solution approach is also proposed based on generalized Benders decomposition. Finally, numerical results obtained from a real-world case of application on the process industry are shown and discussed.

Keywords: spare parts management; supply chain network design; supply chain management, network optimization, inventory control; inventory location problem; generalized Benders decomposition.

1. Introduction

Managing the Spare Parts (SPs) is crucial to achieve the planned goals of the companies. According to researchers and practitioners, managing SPs tends to be substantially different to other items, such as productive supplies, raw materials, or commodities, due to the specific features that characterize their behaviour (Huiskonen, 2001; Cavalieri et al., 2008; Martin et al., 2010; Wagner et al., 2012; Roda et al., 2014). Spare Parts Management (SPM) spans all the SP-related decisions from acquisition to consumption. Thus, most of the SPs literature have been focused on developing tools to support the decision-making processes within SPM. However, some specific and related issues have not been widely addressed in the traditional literature. Among others, Supply Chain (SC) and Supply Chain Network (SCN) related issues have been assumed as given and fixed for most of the analysis made in SPM literature (Huiskonen, 2001; Wagner, et al., 2002, Martin, et al., 2010). Nevertheless, the underlying SCN, which supports the entire SPs operations (e.g., distribution, inventories, warehousing), may significantly impact the SPM performance and the company results.

Accordingly, this paper analyses the integration of Spare Parts Supply Chain Network (SP-SCN) design and control with traditional SPM decision-making processes. This integration is made based on a generic modelling structure that optimizes the warehouse location, Consumption Points (CPs) assignments and inventory control decisions, while minimizing the total system cost, consisting of operation and setting fixed costs, transportation costs, and inventory costs. Particularly, this paper discusses some general relationships among traditional SPM, SP inventory management, and SCN design and management decisions.

Notice that a CP is intended to be a portion of the entire production process that generates a demand for SPs. This portion can be clearly defined and delimitated, such as a component, a machinery, an entire process, an entire plant. Therefore, it is assumed that these CPs are the final echelon of the SP-SCN, i.e., assets in the industrial plant located at the end-user site associated with production activities that consume SP for replacements purposes when facing preventive maintenance activities or failure events.

In addition, as in Tapia-Ubeda et al. (2018a), this paper proposes a generic modelling structure for a single-SP system aimed at optimizing the SP-SCN by jointly considering warehouse location and inventory control decisions, based on a generic Inventory Control Policy (ICP). This structure aids to identify relevant issues that must be embraced and formulated into specific models. These specific models are derived based on the generic model for each specific ICP.

The proposed modelling structure allows to address two relevant sets of decisions, one set related to the SCN design and other set related to the ICP considered for managing the SP inventories across the SP-SCN. Particularly, SCN design-related decisions are consistent with the standard and widely studied Facility Location Problems (FLPs) structure (Daskin, 1995; Drezner, 2002; Melo et al, 2009; Eiselt and Marianov, 2011). The generic model is specified based on three ICPs commonly adopted for managing SPs inventories in industrial settings, yielding three specific network optimization models. Notice that, the generic modelling structure, and consequently the specific models, belongs to the family of Inventory Location Problems (ILPs). Typically, ICPs models integrate warehouse location and inventory control decisions while minimizing the total systems costs (Erlebacher and Meller, 2000; Daskin, et al., 2002; Miranda and Garrido, 2004; Farahani et al., 2015).

One of the main objectives of this research is to support the SP-SCN design and control decision-making process in real-world industrial settings. Hence, solution approaches to effectively and efficiently solve the optimization models are strongly required. Accordingly, and following Tapia-Ubeda et al, (2018b) and Geoffrion (1972), this paper proposes a generic solution approach based on the Generalized Benders Decomposition (GBD) aimed at solving the general modelling structure proposed in this paper. Notice that, the approach in Tapia-Ubeda et al, (2018b) was developed to solve an Inventory Location problem with a single and specific ICP, i.e. (s, Q), and then is not straight applicable to the general model introduced in this paper and in Tapia-Ubeda et al. (2018a) . Thus, the proposed solution approach represents a generalization of the algorithm in Tapia-Ubeda et al. (2018b), denoting a relevant contribution of this paper.

Finally, a thorough discussion is made going further into the relationships between the mathematical models, the SPM and the SP-SCN. Consequently, a research agenda is presented considering different features that can be integrated into the mathematical models.

This document is organized as follows. Section 2 presents the literature review of the related topics. Section 3 is focused on presenting and discussing the decisions encompassed by the Spare Parts Supply Chain (SP-SC). The generic modelling structure and the specific models are presented in Section 4. Section 5 is aimed at presenting a solution approach based on GBD to solve the proposed generic model. The general description of an industrial application and results are presented in Section 6. Finally, Section 7 is focused on presenting the conclusions of this research and the perspectives for future research.

2. Literature review

The specificities of the SPs generate requirement for dedicated approaches to properly manage them. Accordingly, SPM must deal with peculiar characteristics, which makes it especially difficult in industrial settings. In general, the decisions considered on SPM should be addressed by integrating specific SPs aspects (e.g., criticality, demand pattern, specificity, price, stock-out cost). Typically, the related literature on SPM has been focused on these aspects but addressing them separately. Even so, it is possible to find related papers that integrate different aspects of SPM highlighting the relationships between them (Huiskonen, 2001; Cavalieri et al., 2008; Boylan and Syntetos, 2010; Martin et al., 2010; Wagner et al., 2012; Roda et al., 2014; Driessen et al., 2015; Durán et al., 2016, Hu, et al., 2017). Moreover, some of these papers highlight the relevance of considering more holistic and multidisciplinary approaches as an opportunity to improve the SPM performance (Huiskonen, 2001; Martin, et al., 2010). Nevertheless, the related literature focuses mainly on single-location techniques instead of multi-location approaches that integrate these aspects.

Among all the related aspects, SPs classification is commonly used in real industrial cases, where criticality and demand pattern may be crucial elements to be considered. Outcomes of classification techniques are used to select the ICP to be used and some related decisions (e.g., re-order points, order sizes, service levels), maintenance strategy, among others. Despite its strong relevance, classification is still an open discussion, and a wide variety of approaches and techniques can be found on the related literature (Braglia, et al., 2004; Roda, et al., 2014). The selection of the proper ICP to manage the SPs is a critical decision for SPM (Roda et al., 2014; Durán et al., 2016). Considering the demand nature of most of the SPs, typical ICP models may not be suitable to manage SP inventories (Kennedy, et al., 2002; do Rego and De Mesquita, 2011; Driessen, et al., 2015; Bounou, et al., 2017).

More specifically, it is worth remarking that the demand pattern of the SPs is one of the characteristics that made these parts different from other materials and products. The intermittent nature of the demand pattern is a common feature in most of the SPs behaviours. The unavailability of the SPs can lead to downtimes that generate strong consequences on the global performance (Cavalieri et al., 2008; Syntetos, et al., 2012; Roda et al., 2014). Then, inventories of SPs are required to ensure the availability of the system. Accordingly, this issue has received special attention in the literature. Most of the papers are focused on the application of inventory theory on the SPs specific contexts. The most common approach to select the ICP is driving it by the classification technique used to segregate the SPs. Consequently, it is possible to understand some of the relationships between the specific features of a SP class and the most suitable ICPs (Kennedy, et al., 2002; Braglia, et al., 2004; Cavalieri, et al., 2008; do Rego and De Mesquita, 2011; Bounou, et al., 2017).

On the other hand, SC is one of the main concerns for companies especially for the impact on global performance. Consequently, Supply Chain Management (SCM) became an important field of literature and in practice. SCM involves decisions related to the activities, processes, and resources required to be efficiently and timely managed (Simchi-Levi, et al., 2003; Coyle, et al., 2003). Particularly, the SCN design has a significant impact on the global performance (Miranda and Garrido, 2004; Shen, 2007; Melo et al., 2009; Farahani, et al., 2014). Applying the general knowledge of SCM over SPM, to accomplish the proposed goals, the company needs to coordinate the SP-SC considering all the involved activities. However, the SP-SC must not be only focused on the internal activities and processes, indeed this normally spans links with third parties (Huiskonen, 2001; Frazzon, et al., 2014). The SP-SCN has not been widely studied in the related literature. Most of the works that integrate SPs with SC are in fact focused on the processes across the SP-SC, but do not consider the relationships with the SP-SCN structure (Huiskonen, 2001; Rosseti and Thomas, 2006; Martin et al., 2010; Wagner, et al., 2012).

It is worth pointing out that most of the papers on SCM are focused on products (e.g., raw materials and finished products) considering the inbound and outbound logistics (Tracey, et al., 2005; Wu, et al., 2006; Tsao and Lu, 2012). On an SCN design context, one of the key decisions is facility location. Consequently, Facility Location Problems (FLPs) have been widely studied in the literature. Naturally, strategic decisions related to FLPs impact on the long-term horizon (Coyle et al., 2003; Snyder, 2006). Mainly based on FLPs, Inventory Location Problems (ILPs) typically integrate the location of facilities, customer assignment, and inventory control decisions. This integration should lead to better solutions, but it incorporates complexity on the mathematical models (Jayaraman, 1998; Farahani, et al., 2015). Transferring this general knowledge to SPM is worth as research particularly due to extant gaps.

Jayaraman (1998) introduces an ILP analysing the relationships among transportation, facility location and inventory control decisions. Erlebacher and Meller (2000) integrates facility location and inventory control policy decisions introducing a mixed integer nonlinear model. Later, Daskin et al. (2002) and Miranda and Garrido (2004) incorporate safety stock into their models considering the variability of the customers' demand. Shen et al. (2003) incorporates risk pooling aspects. Miranda and Garrido (2006) incorporates stochastic capacity constraints based on chance constraint. Miranda and Cabrera (2010) and Cabrera et al. (2013) present a novel problem with stochastic capacity constraints considering a periodic review policy for the inventories. Arabzad et al. (2015) introduces a multi-objective model that incorporates different transportation modes and third-party logistics. Escalona et al. (2015) considers a differentiated service level considering two de- mand classes using a critical level policy. Shu et al. (2015) presents an ILP that integrates warehouse location, warehouse-retailer assignments decisions over an infinite planning horizon. Manaktar et al. (2016)

introduces a multi-echelon multi-commodity ILP. Ahmadi et al. (2016) presents a multi-commodity capacitated three-echelon model with transhipment options. Li et al. (2018) introduces an ILP in a closed-loop system with third-party logistics.

Integrating decisions as performed in this research leads to models with higher complexity. Thus, developing effective and efficient solution approaches is crucial to solve these integrated models. Through the last decades several solution approaches have been developed to solve different ILPs in the literature. According to Ağrali et al. (2012) the most popular solution approaches developed to solve ILPs have been Lagrangian relaxation and greedy heuristic based algorithms. Different Lagrangian relaxation algorithms for different ILPs are presented in Daskin et al. (2002); Miranda and Garrido (2004, 2006, 2008); Snyder et al. (2007); Ozsen et al. (2008); Diabat et al. (2015) and Araya-Sassi et al. (2018). On the other hand, several heuristic algorithms are shown in Erlebacher and Meller (2000); Guerrero et al. (2013); Zhang et al. (2014); Nekooghadirli et al. (2014); Ghorbani and Akbari Jokar (2016); Tavakkoli-Moghaddam and Raziei (2016); Perez-Loaiza et al. (2017), Fontalvo et al. (2017) and Li et al. (2018). Shen et al. (2003) proposes a set covering reformulation and a column generation-based solution approach. Shu et al. (2015) presents a cutting-plane approach based on the submodular property of costs terms considered in the problem. Arabzad et al. (2015) presents an approach simultaneously considering genetic algorithm and simulated annealing. Manatkar et al. (2016) presents a hybrid algorithm based on multi-objective particle swarm and genetic algorithm. Wheatley et al. (2015) presents and algorithm based on Benders Decomposition for solving an ILP with nonlinear service constraints. Ağrali et al. (2012) presents an algorithm based on GBD for an ILP where a hybrid algorithm based on outer approximation is used. Finally, Tapia-Ubeda et al. (2018b) presents an algorithm based on GBD for solving an ILP with stochastic capacity constraints. This paper extends the work of Tapia-Ubeda et al. (2018b) by developing a GBD-based solution approach for the generic model proposed in this paper, solution approach that can be applied for any ICP.

3. Decisions within spare parts supply chain

According to Simchi-Levi et al. (2003), SC is a system consisting of suppliers, manufacturers, transportation, distributors, and vendors that exists to transform raw materials to final products and supply those products to customers. SCM is focused on the efficient integration of SC's components to produce and distribute right quantities to the right locations at the right time. This should be made minimizing the total system costs and satisfying customers' requirements.

According to Harland et al. (2001), both SC and SCN describe the flows (i.e., materials and information) between the diverse components, but SCN describes a more complex structure (see Fig. 1). In general, SC describes a simpler and sequential set of links, SCN considers where organizations can be cross-linked, and there are two-way exchanges between them.

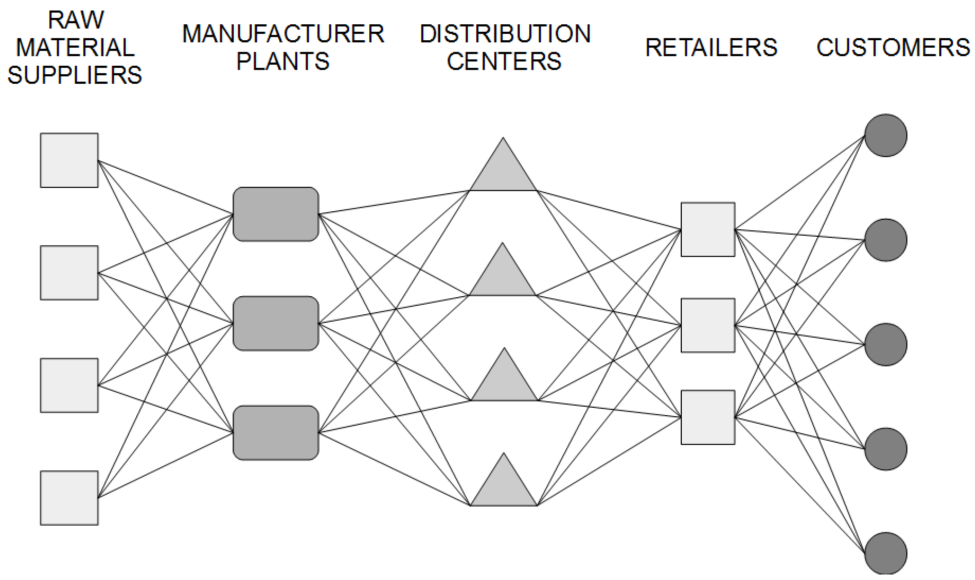

Fig. 1. A Generic Supply Chain Network

On the other hand, SPM spans all the decisions from the purchase to the use or consumption of the SPs. Consequently, these decisions consider procurement, inventories, logistics, and supply chain. One of the main issues for the SPM is to minimize the unexpected downtimes supplying the required SPs at the right place and time. Consequently, to properly respond to this issue the decisions cannot be made in isolation and it is required to consider the impact of each aspect on the other decisions (Huiskonen, 2001; Martin et al., 2010; Wagner et al., 2012; Driessen et al., 2015).

According to these definitions, SC can be considered as a relevant part of SPM for ensuring efficiency and continuity of productive activities. Moreover, in the other side, SCM perspective and approaches are quite proper to enable SPM purposes. However, only a few studies go further in this analysis (Huiskonen, 2001; Wagner, et al., 2002; Martin, et al., 2010). With this aim, the focus of this paper is understanding and studying the SP-SC, and the related network design problems. Therefore, according to the previous discussion about SPs peculiarities in Section 2, it is expected that due to the specific characteristics and behaviors of the SP, different SCN structures will fit better for different SP classes. Huiskonen (2001) highlights the relevance of the inventory location from a logistic perspective. Wagner et al., (2002) gives a similar discussion distinguishing between central and local inventories based on the SP characteristics. In general, it is assessed in the literature that different classes of SPs can be identified within a company based on multiple-criteria (e.g., like price, lead time, stock-out cost and specificity) and depending on the criticality of the class they should be managed differently (Roda et al. 2014).

Considering that different SCN structures may fit better with different SP characteristics, it is worth to consider the availability of network optimization modeling structures that enable to cope with different needs of the variety of SPs classes. Fig. 2

presents a generic SP-SCN, considering SPs’ suppliers, internal warehouses, and consumption points. Internal warehouses are the set of facilities located to serve the demand generated from inventories. In general, a consumption point can be defined as a production activity that consumes SPs for replacements purposes. This structure is derived from the related literature that addresses some SP-SCN issues (Huiskonen, 2001; Martin, et al., 2010), but also considering the structure assumed by the proposed models.

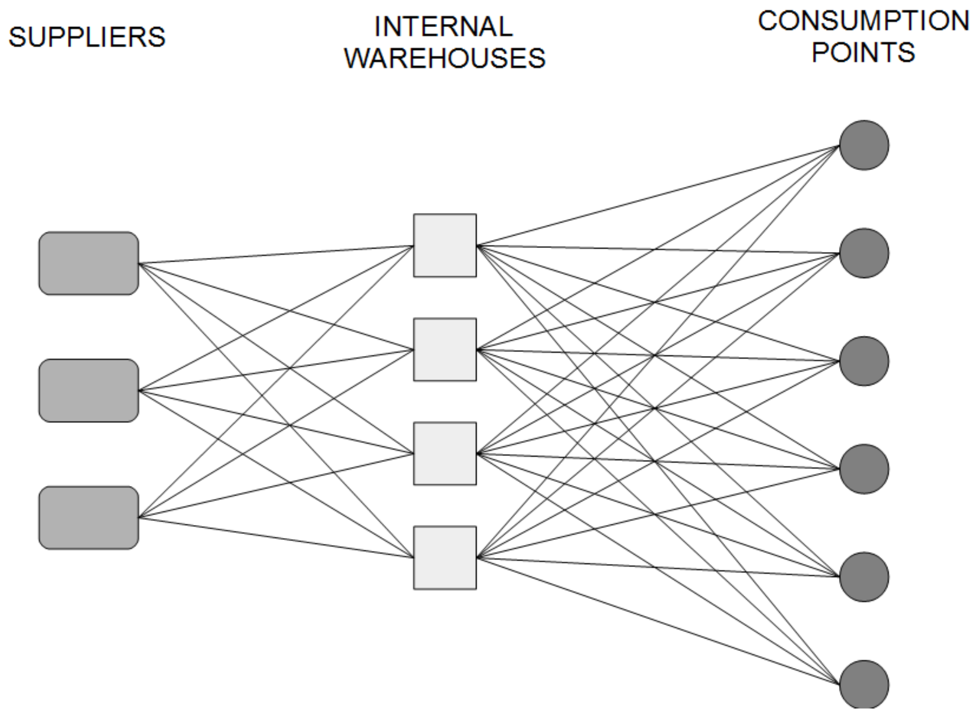

Fig. 2. A Generic Spare Parts Supply Chain Network

4. Supply chain network optimization models

This section is focused on presenting a generic single-commodity model based on a joint warehouse location and inventory control modelling structure to optimize the SP-SCN. Additionally, three models, derived from the generic model, considering three different ICPs are presented.

4.1 A Generic Modelling Structure

The proposed generic model relies on a common modelling and network structure of a typical FLP. It is assumed that the set suppliers is fixed and known. Additionally, the model assumes that all the warehouses follow the same ICP. This model is focused on jointly optimizing the warehouse locations, the consumption point assignments and the inventory control decision. The warehouses selected to operate will store the SP inventories, which are design to serve the demands generated at each CP assigned to each warehouse. Inventory control decisions are related to sizing the inventory level for each warehouse. The demand that each warehouse faces corresponds to the aggregation of CP demands assigned. The CP demands are characterized by its mean and variance. Finally, the generic model aims to minimize the total cost of the SP-SCN.

The decision variables are:

X_i	Binary variable. It values 1 if a warehouse is located on site *i*, 0 otherwise.
Y_{ij}	Binary variable. It values 1 if the consumption point *j* is assigned to the warehouse *i*, 0 otherwise
D_i	Demand mean served by the warehouse *i*
V_i	Variance of the demand served by the warehouse *i*

The parameters and the sets are the following:

FC_i	Setting and operational fixed cost of a warehouse on location *i*
CIn_i	Inbound transportation cost of a warehouse on the location *i* (from a known source or spare parts provider)

$COut_{ij}$	Outbound transportation cost of a warehouse on location *i* to serve user *j*
μ_j	Mean of the spare part demand of the consumption point *j*
σ_j	Variance of the spare part demand of the consumption point *j*
N	Set of potential warehouses
M	Set of consumption points (i.e. the assets operating in the industrial plant at the end-user site)

Then, the generic model structure is as follows:

$$Min \quad \sum_{i\in N} FC_i \cdot X_i + \sum_{i\in N}\sum_{j\in M}\left(CIn_i + COut_{ij}\right)\cdot \mu_j \cdot Y_{ij} + \sum_{i\in N} TC\text{-}ICP_i^p\left(D\left(X,Y\right),V\left(X,Y\right)\right) \qquad (1)$$

s.t.:

$$\sum_{i\in N} Y_{ij} = 1 \qquad \forall j \in M \qquad (2)$$

$$Y_{ij} \le X_i \qquad \forall i \in N, \forall j \in M \qquad (3)$$

$$D_i = \sum_{j=1}^{M} Y_{ij}\cdot \mu_j \qquad \forall i \in N \qquad (4)$$

$$V_i = \sum_{j=1}^{M} Y_{ij}\cdot \sigma_j \qquad \forall i \in N \qquad (5)$$

$$X_i, Y_{ij} \in \{0,1\} \qquad \forall i \in N, \forall j \in M \qquad (6)$$

Expression (1) represents the objective function that corresponds to the total SCN costs. The first term represents the setting and operating fixed costs for all warehouses. The second term is the total transportation costs (provider – warehouses and warehouses – end-users). Finally, the term $TC\text{-}ICP_i^p\ (D(X,\ Y),\ V(X,\ Y))$ represents the total cost associated with the ICP type *p* for the warehouse on location *i* depending on the mean and variance of the assigned CPs' demand. Equations (2) ensure that each consumption point must be served by a single warehouse. Constraints (3) ensure that the users are assigned only to installed warehouses. Equations (4) and (5) compute demand mean and variance that must be served by each warehouse. Equations (6) represent the binary domain of the SCN decision variables.

4.2 Specific models

To adapt the generic model to the specific needs of a variety of SP classes, this paper also presents three specific formulations derived from the basic model structure by considering specific ICPs. For each specific formulation, it is required to define additional parameters and decisions variables. It is required to be mentioned that a Normal approximation is assumed to model demands at the consumption points and warehouses. The additional parameters are:

OC_i	Fixed ordering cost for the warehouse in the location *i*
HC_i	Unitary holding at a warehouse in the location *i*
LT_i	Lead time for an incoming order to the warehouse in the location *i*
α	Minimum required stock-out probability at each warehouse
$Z_{1-\alpha}$	Standard normal distribution value that accumulates $1-\alpha$

The specific main decision and auxiliary decision variables are as follows:

Q_i	Order quantity for the warehouse *i*
U_i	Undershoot at the warehouse *i*
S_i	Maximum objective inventory level for the warehouse *i*

s_i Re-order point for the warehouse i

Notice that these variables are not considered for all the models. The variables that are considered on each specific model depend on the employed ICP.

Additionally, just as considered in most of the traditional inventory and SPM literature, when an order is submitted the inventory level should cover the demand generated during the lead time with a probability $(1 - \alpha)$. This probability is known as the inventory service level, and α is defined as the stock out probability.

a) Continuous Review (s, Q)

The first model considers a continuous review with a fixed order quantity policy (Q). The re-order point s defines the inventory position when a replenishment order must take place. When the inventory level reaches the re-order point, an order of size Q is submitted. This order arrives after the lead time. In this case, the total cost of the ICP for each warehouse can be expressed as follows:

$$TC\text{-}ICP_i^a\left(D\left(X,Y\right),V\left(X,Y\right)\right)=\left(\frac{OC_i\cdot D_i}{Q_i}+\frac{HC_i\cdot Q_i}{2}\right)+HC_i\cdot Z_{1-\alpha}\cdot\sqrt{LT_i}\cdot\sqrt{V_i} \quad (1a)$$

The first term represents the ordering costs and holding costs of cycle inventory. The second term represents the safety stock cost.

b) Periodic Review (R, s, S)

The second specific model considers a periodic review with a variable order quantity policy. In this policy, the stock level is reviewed at the end of a fixed period of R units of time. If there are less or equal units than the re-order point (s) a replenishment order is submitted. The size of the order is aimed to return the stock level to the maximum objective stock level (S). Accordingly, the order size is variable and depends on the inventory level $I(t)$. If an order must be submitted, the difference between re-order point and the inventory level is known as undershoot (U). The average undershoot, as a function of demand mean and variance of warehouse i, D_i and V_i, and for a review period R_i, can be computed as showed in (7). For this ICP, (1) can be expressed is as follows:

$$TC\text{-}ICP_i^b\left(D(X,Y),V(X,Y)\right)=\left(\frac{OC_i\cdot D_i}{(Q_i+U_i)}+\frac{HC_i\cdot(Q_i+U_i)}{2}\right) + HC_i\left(D_i\cdot R_i+Z_{1-\alpha}\cdot\sqrt{LT_i+R_i}\cdot\sqrt{V_i}-U_i\right) \tag{1b}$$

The first term represents the ordering cost and holding cost of cycle for a variable lot size (Q_i + U_i), where Q_i is computed as the Economic Order Quantity. The third term represents the safety stock cost.

$$U_i=\frac{V_i}{2\cdot D_i}+\frac{D_i\cdot R_i}{2} \qquad \forall i=1,\ldots,N \tag{7}$$

c) Continuous Review (S-1, S)

The third specific model considers a continuous review ICP known as “one for one replenishment policy”. Whenever a demand arises, a replenishment order is submitted. The order size depends on the number of units consumed. Nevertheless, the demand for an SP may behave as a one by one demand process. In this case, (1) is expressed as follows:

$$TC\text{-}ICP_i^c\left(D(X,Y),V(X,Y)\right)=OC_i\cdot D_i+HC_i\cdot\left((S_i-1)-D_i\cdot LT_i\right) \tag{1c}$$

The first term considers the ordering cost that it is assumed each time that a demand arises. The second term represents the holding cost.

5. Generalized Benders Decomposition-based solution approach

Mainly based and focused on the generic modelling structure presented in Section 4.1, and also considering the outcomes and the approach introduced in Tapia-Ubeda et al. (2018b), this paper proposes a Benders decomposition-based solution approach. Then, this section is aimed at showing the proposed decomposition approach to solve the generic model. Subsequently, some specific insights are discussed for the three specific models presented in Section 4.2.

Geoffrion (1972) introduces the GBD devoted for solving nonlinear convex optimization problems. This solution approach assumes that the decision variables of the problem can be decoupled into two disjoint sets, i.e. complicating and non-complicating variables. It is also assumed and required that the problem is significantly easier to solve when the values of the complicating variables are fixed and known. Thus, the complicating variables are encompassed by the Master Problem (MP), while the non-complicating variables belong to the Sub-Problem (SbP). Defining a set of dual multipliers related to SbP's constraints, it is possible to build the related SbP's dual-Lagrangian problem. Then, based on the optimal solution of the SbP and its dual, it is a constraint or cut is built in order to be iteratively added into the MP. Therefore, the problem is solved iteratively based on the addition of the cuts.

In this case, it is assumed that the MP variables (complicating variables) are the supplier selection and SCN design variables, i.e. X and Y. Consequently, the SbP variables (non-complicating variables) are D and V. It is worth to be mentioned, that each specific ICP may define additional variables to represent the specific inventory control variables. Notice that, although D and V do not represent real decision variables to be addressed by the decision maker, based on the proposed decomposition approach, these variables arise as decisions variables of the SbP.

Temporarily fixing a set of feasible values for the MP variables, i.e. $\bar{X}, \bar{Y}$, the SbP can be written as is shown in (8)-(10).

$$Min \quad \sum_{i\in N} TC\text{-}ICP_i^p\left(D\left(\bar{X},\bar{Y}\right),V\left(\bar{X},\bar{Y}\right)\right) + \sum_{i\in N} FC_i \cdot \bar{X}_i + \sum_{i\in N}\sum_{j\in M}\left(CIn_i + COut_{ij}\right)\cdot \mu_j \cdot \bar{Y}_{ij} \tag{8}$$

s.t.:

$$D_i = \sum_{j=1}^{M} \bar{Y}_{ij} \cdot \mu_j \qquad \forall i \in N \tag{9}$$

$$V_i = \sum_{j=1}^{M} \bar{Y}_{ij} \cdot \sigma_j \qquad \forall i \in N \tag{10}$$

Assigning the dual-Lagrangian multipliers $\lambda1$ and $\lambda2$ to the constraints (9) and (10) respectively stemmed ($\lambda1_i^k, \lambda2_i^k$ for each warehouse i and for each iteration k) a dual-Lagrangian problem is built. Solving this SbP and its dual-Lagrangian problem allows to obtain the cuts that will be iteratively added into the MP. Therefore, the set of optimality cuts at iteration k can be written as shown in (11). It is worth to be mentioned that the proposed solution approach does not incorporates feasibility cuts by ensuring the feasibility of the SbP at each iteration by adding valid inequalities into the MP (see Tapia-Ubeda et al., 2018b). Notice that $\bar{D},\bar{V},\bar{\lambda}$ denotate fixed and known values for the SbP variables.

$$\begin{aligned} \eta \geq & \sum_{i\in N} FC_i \cdot X_i + \sum_{i\in N}\sum_{j\in M}\left(CIn_i + COut_{ij}\right)\cdot \mu_j \cdot Y_{ij} \\ & + \sum_{i\in N} TC\text{-}ICP_i^{pk}\left(D\left(X,Y\right),V\left(X,Y\right)\right) \qquad \forall k \in P^k \\ & + \sum_{i\in N} \overline{\lambda1_i^k} \cdot \left(\sum_{j=1}^{M} Y_{ij} \cdot \mu_j - \overline{D_i^k}\right) + \sum_{i\in N} \overline{\lambda2_i^k} \cdot \left(\sum_{j=1}^{M} Y_{ij} \cdot \sigma_j - \overline{V_i^k}\right) \end{aligned} \tag{11}$$

Considering that the set $P^{k=0}$ is initially empty, the initial MP is unbounded. Then, an initial MP's feasible solution is found by using an auxiliary MP. Thus, the SbP and its dual-Lagrangian problem are solved considering the initial solution to build the first optimality cut. Accordingly, the MP at iteration k can be written as shown in (12).

$$\begin{aligned} &Min \quad \eta \\ &s.t.: \\ &\qquad (2),(3),(6),(11) \end{aligned} \tag{12}$$

The MP results to be a Mixed-Integer Problem that can be solved by using a commercial solver. On the other hand, solving the SbP at each iteration depends on the specific cost function related to the ICP *p*.

The general algorithm starts by solving the auxiliary MP and obtaining an initial solution in terms of variables *X*, *Y* and η (where η is unbounded). Based on these values, the SbP and its dual-Lagrangian problems are solved. These values are used to build the optimality cuts at each iteration. The optimality cut build at each iteration is added into the MP. This algorithm ends when the optimality conditions are observed.

6. Industrial case of application

This section is focused on illustrating the industrial case of application. The case concerns a leading global manufacturer of steel pipe products. The plant where the application is made corresponds to the biggest production site owned by the company in Italy. In this plant the whole production process for pipes is performed.

The company classifies the SPs by considering four criticality classes, i.e. strategic (STR), critic (CRI), desirable (DES), and uncritical (UNC). For each of these SP classes a required service level is defined. The company currently operates under a completely centralized structure, i.e. a centralized warehouse stores all the SPs inventories serving all the CPs demand. However, the company was interested on analysing other options: i) completely decentralized structure, where the SPs inventories are stored at small warehouses dedicated for serving a specific CP demand; ii) on-demand structure, where all the demand is directly served from suppliers by using a direct shipment distribution strategy. These three structures are compared with the hybrid structures that is obtained by using the proposed mathematical models in Section 4. A hybrid structure is mainly defined as all the structures that do not belongs to the other three considered structures. In a hybrid structure it is possible to open intermediate warehouses or a mix among centralized, decentralized and intermediate warehouses.

For this case of application, a set of fourteen SPs were selected (4 SPs from STR criticality class, 3 SPs from CRI criticality class, 4 SPs from DES criticality class, and 3 SPs from UNC criticality class). Based on company decision, this application considers the use of the three ICPs used to specify the models in Section 4.2. This application also incorporates two different distribution strategies, i.e. warehousing and direct shipment. The warehousing strategy includes the location of warehouses that are served directly from suppliers and that serve the CPs demands from inventories. On the other hand, the direct shipment considers that CPs are directly served from suppliers avoiding the warehouse operations. Based on the SP classes defined by the company, four different service levels were used for the application, i.e. 99% for the STR class; 96% for the CRI class; 93% for the DES class; and 85% for the UNC class.

Mainly based on SCN structures considered, four main scenarios were generated: scenario 1 considers an on-demand structure; scenario 2 considers a completely centralized structure; scenario 3 considers a completely decentralized structure; and scenario 4 considers a hybrid structure. Scenarios 2, 3 and 4 are analysed considering the three selected ICPs. Notice that in the Scenario 1 an ICP is not required. In particular, three values are given for the length of the review period R of the (R, s, S) ICP: $R \in \{2, 5, 10\}$. Furthermore, scenarios 2, 3 and 4 considers sub-scenarios for each considered ICP. Consequently, sub-scenarios 1, 2.1, 2.2, 2.3, 3 correspond to (s, Q), (R=2, s, S), (R=5, s, S), (R=10, s, S), and (S-1, S) respectively. In other words, sixteen combined scenarios are evaluated: On demand (scenario 1), and the three scenarios (2, 3 and 4) with the five ICP sub-scenarios (1, 2.1, 2.2, 2.3, 3).

Each SP is denoted as *C_P*, where *C* represents the criticality class (STR=1, CRI=2, DES=3, and UNC=4) and $P \in \{1, 2, 3, 4\}$. The CPs will be donated as CP_*N* where $N \in \{1, 2, 3, 4, 5, 6, 7\}$.

It worth to mention that costs for the scenarios 1, 2 and 3 are computed numerically without requiring the optimization models, while scenario 4 does require the use of the proposed models (Section 4.2). Table 1 shows a results summary, where the best options (suggested configuration) are highlighted in grey.

Table 1 – Summary of the results obtained

	Selected SP													
Scenario	**1_1**	**1_2**	**1_3**	**1_4**	**2_1**	**2_2**	**2_3**	**3_1**	**3_2**	**3_3**	**3_4**	**4_1**	**4_2**	**4_3**
S1	240.663,83	193.894,88	334.131,57	257.735,70	2.912.221,00	329.891,34	363.476,16	19.133,00	269.698,33	826.215,84	1.006,28	**431,16**	22.315,83	2.351.690,00
S2.1	26.416,00	16.781,00	30.068,00	27.700,00	16.952,00	29.935,00	31.472,00	19.556,00	36.629,00	74.615,00	16.829,00	16.775,00	20.171,00	183.200,00
S2.2.1	26.416,00	16.790,00	30.068,00	27.692,00	16.954,00	29.941,00	31.473,00	19.556,00	35.630,00	74.616,00	16.829,00	16.773,00	20.172,00	183.199,00
S2.2.2	26.425,00	16.807,00	30.070,00	27.722,00	16.966,00	29.952,00	31.494,00	19.557,00	35.635,00	74.621,00	16.830,00	16.780,00	20.172,00	183.199,00
S2.2.3	26.441,00	16.834,00	30.073,00	27.771,00	16.986,00	29.969,00	31.529,00	19.557,00	35.643,00	74.630,00	16.831,00	16.793,00	20.172,00	183.199,00
S2.3	26.428,00	16.810,00	30.076,00	27.835,00	17.005,00	29.958,00	31.521,00	19.579,00	35.679,00	74.710,00	16.832,00	16.787,00	20.559,00	186.131,00
S3.1	16.047,00	6.394,00	19.696,00	17.332,00	6.554,00	19.553,00	21.103,00	9.178,00	25.235,00	64.201,00	6.459,00	6.406,00	9.634,00	171.549,00
S3.2.1	16.049,00	6.423,00	19.701,00	17.325,00	6.587,00	19.574,00	21.106,00	9.189,00	25.263,00	64.249,00	6.462,00	6.405,00	9.805,00	172.832,00
S3.2.2	16.058,00	6.440,00	19.703,00	17.355,00	6.599,00	19.585,00	21.127,00	9.190,00	25.268,00	64.254,00	6.463,00	6.413,00	9.805,00	172.832,00
S3.2.3	16.074,00	6.467,00	19.706,00	17.404,00	6.619,00	19.602,00	21.162,00	9.190,00	25.276,00	64.263,00	6.464,00	6.426,00	9.805,00	172.832,00
S3.3	16.061,00	6.443,00	19.709,00	17.468,00	6.638,00	19.591,00	21.154,00	9.212,00	25.312,00	64.343,00	6.465,00	6.420,00	10.192,00	175.764,00
S4.1	**10.235,00**	**586,00**	**13.884,00**	11.522,00	**734,00**	**13.742,00**	**15.292,00**	**3.368,00**	**19.414,00**	**58.393,00**	**649,00**	596,00	**3.833,00**	**165.769,00**
S4.2.1	10.239,00	595,00	13.885,50	**11.514,00**	737,00	13.747,00	15.293,00	3.368,33	19.415,00	58.394,00	649,30	594,00	3.834,30	165.771,00
S4.2.2	10.245,00	603,00	13.886,00	11.543,00	749,00	13.757,00	15.314,00	3.369,00	19.420,00	58.400,00	649,77	601,00	3.835,00	165.772,00
S4.2.3	10.261,00	639,00	13.890,00	11.593,00	769,00	13.776,00	15.349,00	3.370,00	19.428,00	58.409,00	650,00	613,00	3.838,00	165.775,00
S4.3	10.248,00	616,00	13.891,00	11.657,00	789,00	13.763,00	15.341,00	3.391,00	19.464,00	58.488,00	653,00	608,00	4.220,00	168.701,00

Figure 3 shows the comparison between the costs of both the current situation (best configuration obtained in scenario 2) and the suggested configuration (best configuration among all the scenarios).

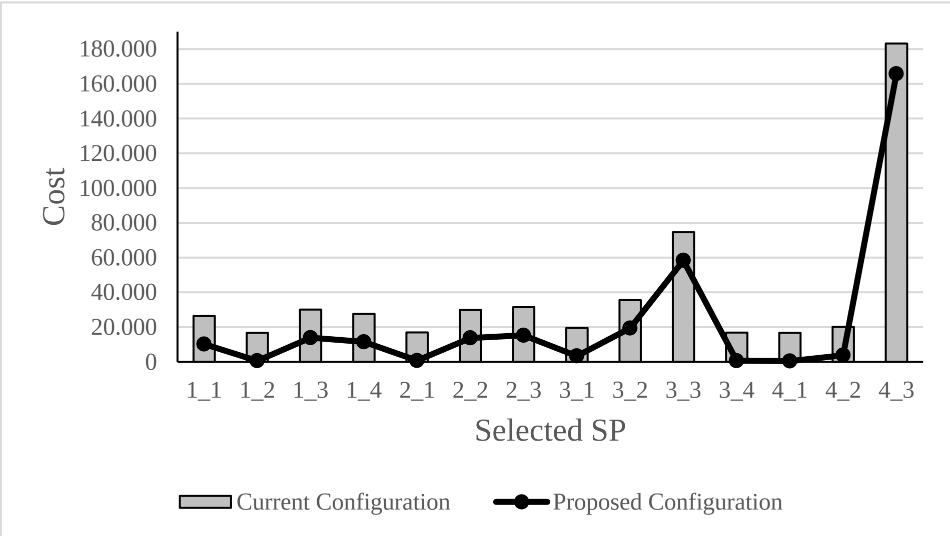

Figure 3 – Comparison between the current and the suggested configurations

Furthermore, the savings percentages of the suggested configuration respect to the current situation are summarized in Table 2.

Table 2 – Saving percentages

SP	**1_1**	**1_2**	**1_3**	**1_4**	**2_1**	**2_2**	**2_3**	**3_1**	**3_2**	**3_3**	**3_4**	**4_1**	**4_2**	**4_3**
Savings [%]	61,3	96,5	53,8	58,4	95,7	54,1	51,4	82,8	45,5	21,7	96,1	97,4	81,0	9,5

It is clear that in almost all the scenarios the best solution is obtained from the hybrid scenarios (scenario 4). The only exception is SP 4_1 where the best configuration is an on-demand structure. Particularly, the current situation is not the best approach for operate the internal SCN. Furthermore, the current situation tends to be worse than the configurations obtained with the other considered scenarios.

Notice that in spite of the SPs selections was performed aiming to represent most of the SPs belonging the same criticality class, these results cannot not directly extend to all the SPs, and further analysis for each SP is still required. In this context, the presented results and methodologies show to be suitable and valid to identify the best (optimal) SCN configuration to manage the SPs, particularly in user sites context.

It is remarkable the significant flexibility of the optimization models that being focused on the hybrid structures (scenario 4) may yield, depending on the system costs, the completely centralized (scenario 2) and completely decentralized (scenario 3) structures as extreme cases. As relevant future research, scenario 1 may be integrated into the model reflecting all the four scenarios with the same model.

7. Conclusions and perspectives

SPs and SPM are well-known issues in decisional problems in industrial practice and, when looking for cost-effective management, they have become relevant to companies, especially in equipment-intensive industries. The related literature has been focused on the specific characteristics and behaviours of SPs and the management subsequently needed. Most of these papers are focused on such specific characteristics considering, in limited scopes, the impact that a decision may have over other decisions. Among them, the SC, SCM and SCN issues have been typically excluded from most of the SPM literature concerned with an end-user perspective (i.e., the owner of the assets in industrial sites). Some authors reflect on the relevance of more integrated approaches to improve the SPM process performance. Then, the integration of different decisions involved in the SPM process may be crucial to improve the global performance, so also the cost-effectiveness.

Having in mind such purpose of integrated decisions, this paper proposes a generic modelling structure integrating SPs warehouse location and inventory control decisions. This model assumes the general structure of the FLPs, where the facility operation is aimed at both holding the SP inventories and serving the CP’s demands. A common ICP is assumed for all the potential warehouses, where the parameters that command the ICP depend on the CPs' assignments. The demand processes are modelled assuming a Normal approximation. Consequently, the CP's demand is represented by the mean and the variance. Then, a generic expression for the cost function is derived. This cost function depends on the ICP and the SCN structure variables (*X* and *Y*). Based on the generic model, three specific ICPs were also considered to derive three specific models. These ICPs are suitable for managing a great variety of spare parts and widely used in industrial settings. It is remarkable that the generic model has the capability to be adapted to different SPs classes. Indeed, each specific model shows the cost function for the particular ICP that depends on the SCN structure variables.

It worth to point out that this paper is based on two foci: i) the impact of related decisions involved into the SPM process and ii) the fact that the integration of decisions makes possible the improvement of SP-SC performance. The first focus is closely related to the hierarchical and sequential structure used to make related decisions; this is also an approach that is well understood in managerial practice. The second focus is, instead, obtained based on a more mathematical perspective, where the optimization models that integrate decisions may enable finding better solutions to improve industry operations. Therefore, having a synergic view of the two foci, this paper leads to include the SCN design issues into the SPM process, thus relating decisions, and to present a generic structure that integrates SCN and inventory decisions, thus creating the potentials for SCM improvement. Overall, this modelling structure can be classified as an ILP model, which then may become mean to bring the SCN design into the SCM process.

The proposal has potential managerial implications and interest for the decision makers. From the SP manager's perspective, this paper shows a structured approach to integrate decisions involved in the SPM process. Moreover, this work is also aimed to generate a direct link between the SP managers and the SCN managers, helping to coordinate, collaborate and improve the SP-SC performance. Such integrated decision-making could be put in practice within a company, after proper data gathering and analysis (e.g. mean and variance of the demand at the spare parts consumption point, etc.).

This paper considers a real-world case of application in the process industry. This industrial case is focused on using the specific models to obtain the optimal spare parts configuration for a specific set of SPs. Each selected SP belongs to a specific criticality class defined by company. The models incorporate the service level requirements defined by the company for each criticality class. The results are clearly show that the current strategy used by company (completely centralized structure) is not the best option to operate the SP-SCN. Furthermore, for almost all the selected SPs the best (suggested) configuration was obtained from the mathematical models. Particularly, in only one case the best option was obtained by considering a on-demand structure. Among all the cases were the optimal configuration was obtained from the mathematical models, the savings range from 9,5% up to 96,5%. Based on these results, it is possible to illustrate the potentiality of using these models in different real-world cases. Furthermore, the models can be crucial for supporting the decision-making process in industrial settings.

For future research, it is possible to include different practical constraints, decisions, and features to make the models more applicable in real-world cases (e.g., capacity constraints, supplier selection, lateral transhipment, multi-commodity, and multi-period). It is also required to develop new specific models considering other suitable ICPs. Future research may also analyse and evaluate the impact of adopting different ICPs on the SPM performances for different SPs' classes.

References

Ağrali, S., Geunes, J., Taşkin, Z.C. (2012). A facility location model with safety stock costs: Analysis of the cost of single-sourcing requirements. Journal of Global Optimization, 54(3), 551-581.

Ahmadi, G., Torabi, S.A., Tavakkoli-Moghaddam, R. (2016). A bi-objective location-inventory model with capacitated transportation and lateral transshipments. International Journal of Production Research, 54(7), 2035-2056.

Arabzad, S.M., Ghorbani, M., Tavakkoli-Moghaddam, R. (2015). An evolutionary algorithm for a new multi-objective location-inventory model in a distribution network with transportation modes and third-party logistics providers. International Journal of Production Research, 53(4), 1038-1050.

Araya-Sassi, C. Miranda, P.A., Paredes-Belmar, G. (2018). Lagrangian Relaxation for an Inventory Location Problem with Periodic Inventory Control and Stochastic Capacity Constraints. Mathematical Problems in Engineering. doi: https://doi.org/10.1155/2018/8237925.

Bounou, O., El Barkany, A., El Biyaali, A. (2017). Inventory Models for Spare Parts Management: A Review. International Journal of Engineering Research in Africa, 28, 182-198.

Boylan, J.E., Syntetos, A.A. (2010). Spare parts management: a review of forecasting research and extensions. IMA Journal of Management Mathematics, 21, 227-237.

Braglia, M., Grassi, A., Monatanari, R. (2004). Multi-attribute classification method for spare parts inventory management. Journal of Quality in Maintenance Engineering, 10(1), 55-65.

Cabrera, G., Miranda, P.A., Cabrera, E., Soto, R., Crawford, B., Rubio, J. M., et al. (2013). Solving a novel inventory location model with stochastic constraints and (R, s, S) inventory control policy. Mathematical Problems in Engineering. doi: 10. 1155/2013/670528.

Cavalieri, S., Garreti, M., Macchi, M., Pinto, R. (2008). A decision-making framework for managing maintenance spare parts. Production Planning & Control, 19(4), 379-396.

Coyle, J.J., Bardi, E.J., Langley, C.J. (2003). The Management of Business Logistics: A Supply Chain Perspective. Quebec: Transcontinental Louisville.

Daskin, M.S. (1995). Network and discrete location: Models, algorithms, and applications. New York, NY: Wiley-Interscience.

Daskin M.S., Coullard C.R., Max Shen Z.J. (2002). An Inventory-location Model: Formulation, Solution Algorithm and Computational Results. Annals of Operations Research, 110(1), 83-106.

Diabat, A., Battaïa, O., Nazzal, D. (2015). An improved Lagrangian relaxation-based heuristic for a joint location-inventory problem. Computers & Operations Research, 61, 170-178.

do Rego, J.R., de Mesquita, M.A. (2011). Spare parts inventory control: a literatura review, Producao, 21(4), 645-655.

Drezner, Z., Hamacher, H.W. (2002). Facility location: Applications and theory. New York, NY: Springer-Verlag.

Driessen, M., Arts, J., van Houtum, G.J., Rustemburg, J.W., Huisman, B. (2015). Maintenance spare parts planning and control: a framework for control and agenda for future research. Production Planning and Control, 26(5), 407-426.

Durán, O., Roda, I., Macchi, M. (2016). Linking the Spare Parts Management with the Total Cost of Ownership: An Agenda for Future Research. Journal of Industrial Engineering and Management, 9(5), 991-1002.

Eiselt, H. A., Marianov, V. (2011). Foundations of location analysis. New York, NY: Springer.

Erlebacher, S.J., Meller, R.D. (2000). The interaction of location and inventory in designing distribution systems. IIE Transactions, 32(2), 155-166.

Escalona, P., Ordonez, F., Marianov, V. (2015). Joint inventory problem with differentiated service levels using critical level policy. Transportation Research Part E, 83, 141-157.

Farahani, R.Z., Rashidi Bajgan, H., Fahimnia, B. Kaviani, M. (2015). Location-inventory problem in supply chains: a modeling review. International Journal of Production Research, 53(12), 3769-3788.

Farahani, R.Z., Rezapour, S., Drezner, T., Fallah, S. (2014). Competitive supply chain network design: An overview of classifications, models, solution techniques and applications. Omega, 45, 92-118.

Fontalvo, M.O., Mazam V.C., Miranda, P.A. (2017). A Meta-Heuristic Approach to a Strategic Mixed Inventory-Location Model: Formulation and Application. Transportation Research Procedia, 25, 729-746.

Frazzon, E.M., Israel, E., Albrecht, A., Pereira, C.E., Hellingrath, B. (2014). Spare parts supply chains’ operational planning using technical condition information from intelligent maintenance systems. Annual Reviews in Control, 38, 147-154.

Geoffrion, A. M. (1972). Generalized benders decomposition. Journal of Optimization Theory and Applications, 10(4), 237–260.

Ghorbani, A, Akbari Jokar, M.R. (2016). A hybrid imperialist competitive-simulated annealing algorithm for a multisource multi-product location-routing-inventory problem. Computers & Industrial Engineering, 101, 116-127.

Guerrero, W.J., Prodhon, C., Velasco, N., Amaya, C.A. (2013). Hybrid heuristic for the inventory location-routing problem with deterministic demand. International Journal of Production Economics, 146(1), 359-370.

Harland, C.M., Lamming, R.C., Zheng, J., Johnsen, T.E. (2001). A Taxonomy of Supply Networks. Journal of Supply Chain Management, 37(3), 21-27.

Hu, Q., Boylan, J.E., Chen, H., Labib, A. (2017). OR in spare parts management: A review. European Journal of Operational Research, Article in Press, 2017, doi: 10.1016/j.ejor.2017.07.058.

Huiskonen, J. (2001). Maintenance spare parts logistics: Special characteristics and strategic choices. International Journal of Productions Economics, 71, 125-133.

Jayaraman, V. (1998). Transportation, facility location and inventory issues in distribution network design: An investigation. International Journal of Operations and Production Management, 18(5), 471 – 494.

Kennedy, W.J., Patterson, J.W., Fredendall, L.D. (2002) International Journal of Production Economics, 76, 201-215.

Li, Y., Guo, H., Zhang, Y. (2018). An integrated location-inventory problem in a closed-loop supply chain with third-party logistics. International Journal of Production Research, 56(10), 3462-3481.

Manatkar, R.P., Karthik, K., Kumar, S.K., Tiwari, M.K. (2016). An integrated inventory optimization model for facility location-allocation problem. International Journal of Production Research, 54(12), 3640-3658.

Martin, H., Syntetos, A.A., Parodi, A., Polychronakis, Y.E., Pintelon, L. (2010). Integrating the spare parts supply chain: an inter-disciplinary account. Journal of Manufacturing Technology Management, 21(2), 2010, 226-245.

Melo, M.T., Nickel, S., Saldanha-da-Gama, F. (2009). Facility location and supply chain management – A review. European Journal of Operational Research, 196, 401

-412.
Miranda, P.A., Cabrera, G. (2010). Inventory location problem with stochastic capacity constraints under periodic review (R, s, S). In International Conference on Industrial Logistics "Logistics and Sustainability": 1 (pp. 289–296).

Miranda, P.A., Garrido, R.A. (2004). Incorporating inventory control decisions into a strategic distribution network design model with stochastic demand. Transportation Research Part E: Logistics and Transportation Review, 40(3), 183 – 207.

Miranda, P.A., Garrido, R.A. (2006). A simultaneous inventory control and facility location model with stochastic capacity constraints. Networks and Spatial Economics, 6(1), 39-53.

Miranda, P. A., Garrido, R. A. (2008). Valid inequalities for Lagrangian relaxation in a inventory location problem with stochastic capacity. Transportation Research, Part E, 44, 47–65.

Nekooghadirli, N., Tavakkoli-Moghaddam, R., Ghezavati, V.R., Javanmard, S. (2014). Computers & Industrial Engineering, 76, 204-221.

Perez-Loaiza, R.E., Olivares-Benitez, E., Miranda, P.A., Guerrero, A., Martinez, J.L. (2017). Supply chain network design with efficiency, location, and inventory policy using a multiobjective evolutionary algorithm. International Transactions in Operational Research, 24, 251–275.

Roda, I., Macchi, M., Fumagalli, L., Viveros, P. (2014). A review of multi-criteria classification of spare parts: From literature analysis to industrial evidences. Journal of Manufacturing Technology Management, 25(4), 528-549.

Rosseti, M.D., Thomas, S. (2006). Object-Oriented Multi-Indenture Multi-Echelon Spare Parts Supply Chain Simulation Model. International Journal of Modelling and Simulation, 26(4), 359-369.

Shen, Z.J., Coullard, C., Daskin, M. (2003). A joint location-inventory model. Transportation Science, 37(1), 40-55.

Shen, Z.J. (2007). Integrated Supply Chain Design Models: A Survey and Future Research Directions. Journal of Industrial and Management Optimization, 3(1), 1 – 27.

Shu, J., Wu, T., Zhang, K. (2015). Warehouse location and two-echelon inventory management with concave operating cost. International Journal of Production Research, 53(9), 2718-2729.

Simchi-Levi, D., Kaminsky, P., Simchi-Levi, E. (2003). Designing and Managing the Supply Chain: Concepts, Strategies and Case Studies. New York, NY: McGraw-Hill.

Snyder, L. (2006). Facility location under uncertainty: a review. IIE Transactions, 38, 537-554.

Snyder, L., Daskin, M.S., Teo, C.P. (2007). The stochastic location model with risk pooling. European Journal of Operational Research, 179(3), 1221-1238.

Syntetos, A.A., Babai, M.Z., Altay, N. (2012). On the demand distribution of spare parts. International Journal of Production Research, 50(8), 2101-2117.

Tapia-Ubeda, F.J., Miranda, P.A., Roda, I., Macchi, M., Durán, O. (2018a). An Inventory-Location Modeling Structure for Spare Parts Supply Chain Network Design Problems in Industrial End-Used Sites. IFAC-PapersOnLine, 51(11), 968-973.

Tapia-Ubeda, F.J., Miranda, P., Macchi, M. (2018b). A Generalized Benders Decomposition based algorithm for an inventory location problem with stochastic inventory capacity constraints. European Journal of Operational Research, 267(3), 806-817.

Tavakkoli-Moghaddam, R., Raziei, Z. (2016). A New Bi-Objective Location-Routing-Inventory Problem with Fuzzy Demands. IFAC-PapersOnLine, 49(12), 1116-1121.

Tracey, M., Lim, J.-S. Vonderembse, M.A. (2005). The impact of supply-chain management capabilities on business performance. Supply Chain Management, 10(3), 179-191.

Tsao, Y.,-C., Lu, J,-C. (2012). A supply chain network design considering transportation cost discounts. Transportation Research Part E: Logistics and Transportation Review, 48(2), 401-414.

Wagner, S.M., Jönke, R., Eisingerich, A.B. (2012). A Strategic Framework for Spare Parts Logistics. California Management Review, 54(4), 69-92.

Wheatley, D., Gzara, F., Jewkes, E. (2015). Logic-based Benders decomposition for an inventory-location problem with service constraints. Omega, 55, 10-23.

Wu, T., Blackhurst, J., Chidambaram, V. (2006). A model for inbound supply risk analysis. Computers in Industry, 57(4), 350-365.

Zhang, Y., Qi, M., Miao, L., Liu, E. (2014). Hybrid metaheuristic solutions to inventory location routing problem. Transportation Research Part E: Logistics and Transportation Review, 70, 305-323.