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**MULTI-PERIOD MULTI-ECHELON INVENTORY  
CONTROL POLICIES FOR HOSPITAL  
PHARMACIES WITH PRODUCT BUNDLING**

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## **Abstract**

Public healthcare is called to reach new levels of efficiency in their operations. Production and operations research can be effectively support efficiency targets. This paper examines the problem of the delivery of products in a hospital from a central pharmacy to internal wards, when products to be delivered are drugs. The problem can be modeled as a multi-period multi-echelon inventory optimization problem. The central pharmacy of the hospital assumes a role of central decision maker for products' purchasing and their distribution to internal wards. To solve the problem we propose both an heuristic and a optimal approach to be compared with the lot for lot based approach implemented in the studied case. The work demonstrate the effectiveness of the approaches. While the proposed heuristic can be used as a simple implementable procedure, the optimization model integrate classical inventory strategies with combinatorial optimization and considers special requirements of products delivery, such as the product bundling. Results and tests performed on real data are reported to evaluate the good performance offered by the developed decision support tool.

*Key words:* healthcare logistics; inventory control; operational research; optimization; supply chain management



## 1. Introduction

Health care issues have been widely discussed both in systems engineering [14, 7] and Operations Research (OR) fields during the last years. In particular for the OR dimension, several studies have faced problems related to hospitals and health care under various aspects: pharmaceutical supply chain [10], surgical assignment and scheduling [2], management and cost containment [4], material management [9]. The reduction of health care cost is a critical point for all the industrialized countries due to the dramatic pressure of public health care costs on public total expenses. These costs are often not optimized due to the complexity of hospital organizations. Managing the hospital processes in a centralized way is a very complex problem; as consequence, often the distribution of products and equipment is far to be optimal and the applied control procedures result to be ineffective to pursue economical sustainability. Moreover a critical point counteracting the cost optimization strategy relies on the nature of the health care based services where the primary objective is not directly connected to the cost optimization but to human health based performance indicators. Indeed, the risk to have scarce resources to operate safely on human life is a concept often difficult to accept for health care service managers. This practically results, for instance, in a great amount of perishable products (such as drugs) and instruments purchased without optimized purchasing plans. Having to account the costs of products and of equipment not used or expired represents one of the greatest inefficiency for the hospitals management. To this aim a lot of optimization systems have been studied to improve the hospital performances in terms of efficiency without decreasing the service level evaluated in terms of health care based performances. In this paper we propose an OR based approach for the optimization of pharmaceutical purchases and distribution inside a hospital, taking into account the particularities of the application field. The presented research is based on the outcomes of a research project whose aim was the re-engineering of the equipment management, information tracking and distributions of products processes of an hospital. In particular, the real data used to test the models implementation are relative to an Italian Hospital located into the Lombardia Region. The Hospital counts 600 beds and about 3000 employees including doctors, nurses and administrative staff, divided into 8 departments that provide health services for a total annual budget of around 400 million Eur. The analysis of this real case described the organization of the products delivery inside the hospital: the system is organized around a central pharmacy responsible for purchases and distribution of products for all wards of hospital. This paper, taking into account the organization structure of the hospital above mentioned, offers a decision support for the central pharmacy and for internal wards with the aim to reduce the hospitals costs due to management of products. The central pharmacy is in charge of the purchase, the storage and the distribution of products towards all wards on the basis of units requested by doctors and nurses. The system can be configured as a multi-echelon supply chain, composed by wards, central pharmacy, and suppliers of products. In the AS IS analysis emerged that, while the products distribution is only partially controlled at the upstream layer (from the supplier to the central pharmacy), at downstream layer (from the central pharmacy to the wards) the control strategy is only driven by urgency requirements. Being the requests not cost driven, there is a break between the procurement policy from the pharmacy and the distribution of products inside the hospital (to the wards). This break, if not resolved, can create mismatches or worse contrasts between the strategies implemented by the central pharmacy to the suppliers (economies of scale) and from the wards to the central pharmacy (single supply). Other issues are given by the particularities of the application field: the need to dedicate specialized personal to manage inventories and orders, when they could be allocated to more urgent duties, and

the often perishable nature of the products which raises holding costs. The proposed model aims to cover these issues introducing a comprehensive model considering as objective function several costs factors: order costs, central pharmacy inventory holding costs, ward inventory holding costs, product costs. The model introduces, moreover, the possibility to select a set of products aggregated in predefined bundles for the replenishment at wards rather than single ordered products. This particularity has been integrated into the optimal model for two main reasons: firstly, this distribution configuration can ensure a great advantage for the hospital in terms of order/delivery costs of products toward the wards; secondly, defining a bundle of products for single cure or disease can offer the possibility of greater control on products consumed compared to cases cured. The introduction of a bundle concept, therefore, is useful to counteract the fragmentation of system on medication management, to facilitate orders and distribution of products between central pharmacy and wards and to increase the control of costs on use of products at level of wards. The proposed model can be compared with classical inventory control policies built over fixed period and fixed quantity basic policies. A generalization of classical heuristics has been implemented in order to offer a direct mode to upgrade the empirical inventory applied to the use case and as a performance test both to the as is case and to the optimal model. We considered a mathematical formulation of the inventory control starting from previous works [5, 11, 18] focusing on the aspects of products aggregation in bundles. The outputs of the model are the order quantities for products to purchase and the time schedule for products assignment to wards that is the inventory control policy. The paper is organized as following. In Section 2 the state of the art related to health care optimization systems is presented. In section 3 the problem is described in detail. Section 4 define both the heuristic and the optimal multi-period multi-echelon inventory polices developed. In section 5 computational experiments results are given for scenario without and with product bundling. Finally, in section 6, conclusions are drawn.

## 2. Literature review

We are observing a change of paradigm in the methods and tools used for analysis and optimization of health care services. An increasing number of works propose Operations Research (OR) based studies and techniques to improve the match between costs and benefit to obtain a high service level in hospitals. In particular the structure of hospital's organization cited analysed in our work, better known as multi-echelon hub and spoke model, is very widespread and retraces different experiences of scientific research [8, 9]. Due to the complexity for controlling the management process of products, several researchers have proposed to approach by using Supply Chain Management (SCM) methods. Among them, noteworthy are the contributions provided by [20], [1], [17], [3], [15] which described in details which problems solved in SCM has been or can be translated successfully in health care contexts, in particular in the management of products and medical materials. The distribution of drugs was treated at least since 1994 by [12] who proposed a model to solve this complex problem reducing the number of carriers for supply distribution used into a Belgian teaching hospital. From the operational side of resources optimization, [2] presented an innovative scheduling problem to surgical scheduling, while [10] discuss the complexity of the inventory managing problem at strategic and tactical level through a general multi-product (s, S) model with space constraints and ordering/inventory costs. Supply problems for internal wards or for supply in health care systems, present common characteristics such as limited resources, capacity constraints, urgency case management and perishable items. Research on supply problems in health care field is often related to inventory

problems. [16] apply inventory models for non-perishable items in health care delivery settings. [11] show that it is possible to classify two kinds of researches on supply problems in health care systems. The first one is related to store, location and delivery of items (products and equipment) considering the system composed by several echelons. This branch solves in a separate manner the supply chain problems; then the different results coming from separate optimization runs of the different health care areas are integrated also by using a proper set of indicators. The second one is a research field that tackle the problem of purchasing, stocking and delivering items in health care system using the integrated supply chain management theory. The authors [11] propose a method to regulate the purchasing and the delivery of products on the basis of a capacity constraints system composed by manpower, storage's volume and weight availability or capacity. [13] compare two products distribution networks: inventory costs and service levels of an in-house three-echelon distribution network vs. an outsourced two-echelon distribution network. [19] consider multiple pharmaceutical products, variable lead time, permissible payment delays, constraints on space availability, and the Customer Service Level (CSL). They develop a procedure for determining optimal solutions for inventory lot size, lead time, and the number of deliveries to achieve hospital CSL targets with a minimum total cost for the supply chain.

A considerable quota of the reviewed works use simulation based approaches [20, 1] instead of optimization because of the problem complexity and due to system stochastics. In these settings the what if analysis can be more applicable into real scenario instead of the best of analysis. Yet, the recent literature focus not more and not only on design or optimization of products and equipment management processes, but also on innovative technologies and software used to support management decisions without changing the internal material flow and organization structure of the hospital [6]. Under this view, technologies such as GPS, RFID and IoT play an important role because they can supply a set of data, today unavailable, which is useful as input of the intelligent system used to support the decisional processes as that proposed in this work. The scientific results presented in this paper are encouraging to reach the objective to reduce the costs of products management; before to implement the proposed model and tool in a real system, it will be necessary to collect an important set of data, and it will be possible only through the use of above mentioned technologies.

### 3. Problem description

Following and extending the models developed in [11, 17], we use a supply chain approach where the main decisions are the time schedule and the quantity of the deliveries. We model the problem inside a hospital with two kinds of agents: 1 (one) central pharmacy CP and  $K$  different wards Ws or local care units to be served with product deliveries. In our case CP is the agent which decides on the total products procurement processes from suppliers to hospitals. Information exchange between agents happens with product prices, and order and holding costs. As depicted in Figure 1, the first layer of the multi-echelon supply chain (Level 0), is composed by the suppliers. The second layer (Level 1) of the supply chain is represented by the central pharmacy. The last one, represented by wards and called Level 2, is composed by all hospitals local units, such as surgery, maternity, orthopedic, etc. In the following, we use as notation the layer number as superscript for layer specific model parameters (such as costs). In the modeled problem, the central pharmacy can purchase products from several suppliers and can delivery to several wards, but wards cannot purchase directly from suppliers.

For each delivery (from suppliers to CP or from CP to Ws) there is a fixed cost (named order cost), depending on: distance, human resources needed, time needed. Moreover, in the model

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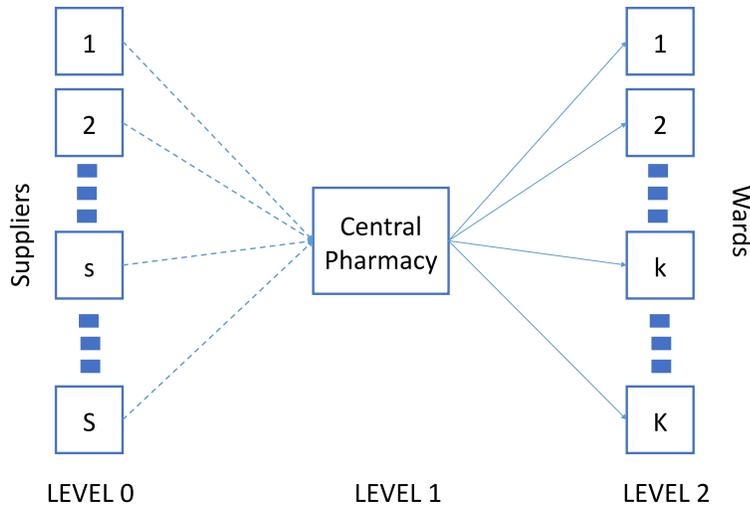


Figure 1: Three-layer hospital products supply chain.

is possible to represent aggregation of several products in bundles. In other words, there is a discount policy from CP to Ws to deliver a set of complementary products rather than in separate way. In addition, some products must be bought and handled coupled resulting in a lower order cost for a bundle is compared to the cost of ordering in a separate way. Suppliers have time dependent production capacity and both central pharmacy and wards have limited inventory capacity. An inventory control policy should produce the following output:

- quantity of products purchased by the Central pharmacy for each time slot, from each supplier
- inventory stocked at central pharmacy for each product
- quantity of products delivered to wards for each time slot
- inventory stocked at wards for each product
- schedule of wards products delivery

The quantity of products delivered to wards for each time slot can be written as number of bundles  $b$  ordered. A bundle store the information about which product to order (eventually coupled with other products), and in which batch. In fact, bundles specify batches (or lots) in which the products must be ordered. In the following section the inventory policies are described.

#### 4. Multi-period multi-echelon inventory policies

The inventory policy adopted was not homogeneous. For some periods and for some products, an empirical  $(s, S)$  based policy has been applied. on the contrary, in most situations the applied policy can be approximated to a lot for lot with a fixed safety stock. While the policies applied (and in particular the lot for lot) is appropriated to avoid stockouts, fixed and variable costs are not considered. This approach can lead to very ineffective inventory control behaviors from

the economic point of view. In the following we define a heuristic and an optimal control policy which can be proposed for the upgrade of the  $(s, S)$  and lot for lot based policies. While the heuristics can be easily implemented in the system, the optimal policy is more general and can manage product bundling based policies.

#### 4.1. Economic Order Quantity based policy

The proposed inventory policy is a generalization of the economic order quantity (EOQ) policy to a multi-echelon supply chain. Starting from the customer orders, EOQ is computed and orders are generated to upstream layer accordingly. in the time dimension  $t$ , the policy produce a backward aggregation of orders guided by economic lot sizing of orders, while in the dimension of the layer  $l$  of the supply chain, the policy produces an upstream propagation of orders. The general inventory policy is sketched in algorithm 1.

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#### Algorithm 1 Multi-echelon EOQ

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1: data: let  $L$  be the number of supply chain layers (with layer 0 the supplier);  $T$  the number
   of planning periods; for each layer  $l$ , let  $d_t^l$  the demand; for each layer  $l$  let  $o^l$  the fixed order
   cost,  $h^l$  the holding cost,  $A^l$  the inventory capacity,  $\bar{d}^l$  the mean received demand during the
   planning horizon.
2: for  $l$  in  $[L, \dots, 1]$  do
3:    $EOQ^l = \left\lceil \sqrt{\frac{2\bar{d}^l o^l}{h^l}} \right\rceil$ 
4:    $q_0^l = 0$ 
5:   for  $t$  in  $[1, \dots, T]$  do
6:      $\delta \leftarrow d_t^l - q_{t-1}^l$ 
7:     if  $\delta > 0$  then
8:        $z_t^l \leftarrow \max\{EOQ^l, \delta\}$ 
9:     else
10:       $z_t^l \leftarrow 0$ 
11:       $q_t^l \leftarrow q_{t-1}^l + z_t^l - d_t^l$ 
12:      if  $q_t^l > A^l$  then
13:         $z_t^l \leftarrow z_t^l - (q_t^l - A^l)$ 
14:         $q_t^l \leftarrow A^l$ 

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The policy computes the temporal aggregation of orders based on the economic order quantity. While aggregating, feasibility checks are performed against the inventory capacities  $A^l$ . The heuristics is designed to be simply applicable and some assumption should be made in order to let the procedure produce feasible solutions. In particular supplier capacity constraint (layer 0) is not considered and the capacity of each upstream layer is assumed to be greater of the aggregation produced by the downstream layer. This assumption can be satisfied in particular in the healthcare applications where the wards warehouse capacity are usually smaller if compared to the upstream pharmacy warehouse capacity. The multi-echelon EOQ policy is defined for a sequential supply chain. Being the studied problem defined on a network with assembly - distribution topology, some adaptations are required for its application. In particular the demand at each layer is computed by summing up on all the layers while the total supply requested at each period is split to the suppliers according to each supplier sorted by their product price proposed. Moreover, the procedure is iterated for each product and product-bundling is not

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considered.

## 4.2. Multi-period multi-echelon model with product-bundling

This section describe a formal optimization model which considers cost minimization and can manage product aggregation in bundles. A bundle  $b$  is a vector of dimension  $I$  where the component  $i$  is equal to 1 if the product  $i$  is considered in the bundle, 0 otherwise. The bundling mechanism models the setting in which operational issues allow to aggregate product orders. For such situations the order cost for an aggregated bundle is subadditive with respect to the products and therefore it is less than the sum of the costs of ordering products separately. In particular, the order cost is payed not for each product ordered but for each bundle ordered. The formulation in the following can be also used to model the scenario where no product bundling is considered. In this case we define exactly  $I$  bundles such that  $b_i = e_i, i \in I$

### 4.2.1. Notation

$S$  set of suppliers;  $s$  index of supplier in  $S$ ;

$W$  set of wards;  $w$  index of ward in  $W$ ;

1 index of the central pharmacy;

$I$  set of products;  $i$  index of product in  $I$ ;

$T$  set of timeslots (time horizon);  $t$  index of timeslot in  $T$ ;

$B$  set of bundles;  $b$  bundle in  $B$ ;

$d_{ikt}$  demand of product  $i$  by ward  $k$  in time period  $t$ ;

$A_{ist}^0$  capacity of supplier  $s$  to supply product  $i$  in period  $t$ ;

$c_{is}$  purchase cost of unit of product  $i$  by Central Pharmacy from supplier  $s$ ;

$o_{is}^1$  fixed order cost for product  $i$  from the Central Pharmacy to supplier  $s$ ;

$h_i^1$  holding cost for stocking one unit of product  $i$  in Central Pharmacy;

$o_{jkt}^2$  fixed cost of ordering one bundle  $j$  of products from ward  $k$  to the Central Pharmacy in period  $t$ ;

$h_{ik}^2$  holding cost for stocking one unit of product  $i$  in the ward  $k$  inventory;

$A_{ist}^0$  capacity of supplier  $s$  for product  $i$  in period  $t$ ;

$A_{it}^1$  capacity of the Central Pharmacy's inventory for product  $i$  in period  $t$ ;

$A_{ikt}^2$  capacity of ward  $k$ 's inventory for product  $i$  in period  $t$ ;

$b_{ij}$  quantity of product (batch)  $i$  in bundle  $j$ .

### 4.2.2. Formulation

The decision variables of the model are listed as follows:

$x_{jkt} = 1$  if bundle  $j$  is delivered at ward  $k$  in period  $t$ , 0 else;

$y_{ist} = 1$  if supplier  $s$  delivers product  $i$  in period  $t$ , 0 else;

$z_{jkt}$  integer positive number of bundle  $j$  ordered from ward  $k$  in period  $t$ ;

$q_{ist}$  integer positive quantity of delivered product  $i$  from supplier  $s$  to Central Pharmacy in period  $t$ ;

$Q_{it}^1$  Central Pharmacy's inventory for product  $i$  in period  $t$ ; positive. This is the inventory profile for Central Pharmacy;

$Q_{ikt}^2$  ward inventory for product  $i$  in period  $t$ ; positive. This is the inventory profile of wards.

The model is the minimization of the total cost  $Z$ :

$$\begin{aligned} Z = & \sum_{i \in I} \sum_{s \in S} \sum_{t \in T} c_{is} q_{ist} + \sum_{i \in I} \sum_{s \in S} \sum_{t \in T} o_{is}^1 y_{ist} + \sum_{k \in K} \sum_{j \in J} \sum_{t \in T} o_{jkt}^2 x_{jkt} + \sum_{i \in I} \sum_{t \in T} h_i^1 Q_{it}^1 \\ & + \sum_{i \in I} \sum_{k \in K} \sum_{t \in T} h_i^2 Q_{ikt}^2 \end{aligned} \quad (1)$$

$$s.t. \quad q_{ist} \leq M y_{ist} \quad i \in I, s \in S, t \in T \quad (2)$$

$$z_{jkt} \leq M x_{jkt} \quad j \in J, k \in K, t \in T \quad (3)$$

$$q_{ist} \leq M A_{ist}^0 \quad i \in I, s \in S, t \in T \quad (4)$$

$$\sum_{s \in S} q_{ist} + Q_{it}^1 \leq A_{it}^1 \quad i \in I, t \in T \quad (5)$$

$$\sum_{j \in J} b_{ij} z_{jkt} + Q_{ikt}^2 \leq A_{ikt}^2 \quad i \in I, k \in K, t \in T \quad (6)$$

$$Q_{it}^1 = Q_{it-1}^1 + \sum_{s \in S} q_{ist} - \sum_{k \in K} \sum_{j \in J} b_{ij} z_{jkt} \quad i \in I, t \in T \quad (7)$$

$$Q_{ikt}^2 = Q_{ikt-1}^2 + \sum_{j \in J} b_{ij} z_{jkt} - d_{ikt} \quad i \in I, k \in K, t \in T \quad (8)$$

The equation (1) is the objective function of the model which minimizes the sum of product costs, fixed order and holding costs for central pharmacy and wards along the time horizon. Equations (2) and (3) connect binary and integer variables. Constraint (4) models the timely dependent supplier product capacity while constraints (5) and (6) describe the inventory capacity for central pharmacy and wards respectively. Constraints (7) and (8) model inventory profile for central pharmacy and wards respectively. The core of the model is the connection among the quantities  $q_{ist}$  ordered by the central pharmacy to the supplier, the number of bundles  $z_{jkt}$  ordered by the wards to the central pharmacy and the time dependent demands at wards  $d_{ikt}$ . These variable and parameters connect all the supply chain while the order costs  $o_{jkt}^2$  represent the time-cost preferences of wards for bundles  $b_{ij}$ . They can be enumerated or can be embedded in an auction procedure as in [5]. In this paper the test is performed against real data in which the products are ordered separately or in heuristically aggregated way.

## 5. Computational experiments

### 5.1. Test case analysis

The EOQ based heuristics has been developing using python language, while the mathematical programming model has been developed with IBM ILOG CPLEX Optimization Studio v 12.5. On the following described test instances, the CPLEX solver was limited in its execution time to 100s. Under this condition the solver was able to find a solution with a gap to the optimal solution less or equal 0.30% for separate bundles and 4% on aggregated bundles. The test machine is a windows PC with Intel<sup>®</sup> Core<sup>™</sup> i7-2670QM 2.20 GHz processor with 8 GB RAM. The input of data is done automatically through preformatted excel files. Computational experiments have been conducted with three main aims: compare the as is applied solution with the heuristic and the optimized one, to conduct sensitivity analysis on labor costs effects for the system, and to study the effect of aggregated product-bundles. The analyzed system consists of a central pharmacy serving 7 different wards of the same hospital using procurement from 3 different main suppliers based on real situation. The analysis has been focused on 8 different pharmaceutical products also with real data. To simplify the analysis, the monitoring was done in a time horizon divided in 12 equal timeslots. The holding costs for the central pharmacy  $h_i^1$ , and of the wards,  $h_{ik}^2$ , have been evaluated as a percentage of the cost of the products per year. In particular, for the core comparison,  $h_i^1$  has been set equal to 8.30% of the product mean cost, while  $h_{ik}^2$  has been set equal to 16.33% of the product mean cost. Other crucial parameters are the ordering costs. Its evaluation must be connected to the time spent on the management and the receiving of the order. The standard analysis considers an initial value of 10 for the central pharmacy and 20 € for the internal wards; for sensitivity analysis, basic scenario is designed around the described real case studies where the costs are valued as said and bundles are separated. This scenario is named in the following as S\_A1B1 and the data extracted from the historical inventory policies applied is referred as Scen\_R1.

### 5.2. Results and comparison of policies

The as is scenario S\_A1B1 has been compared with historical data of replenishment orders (Scen\_R1) gathered during a national research project. Substantial improvements in the optimized solutions can be put in evidence if compared to the original one, essentially because the replenishment policy was not optimized at all. While Scen\_R1 corresponds to a solution of 119,850 €, multi-echelon EOQ heuristic produce a solution of 80653.46 €, on Scenario S\_A1B1 and the optimal model generates a solution of 59,695.47 €. This difference against the as is solution, as detailed in table 1, is essentially due to the minor quantity of product needed to cover requirements (and purchased) with the consequent lower inventory costs for central pharmacy.

The optimization model has better performances against the as is scenario but also against the multi-echelon EOQ under all aspects. As shown in Figure 2 in particular for order costs at pharmacy and holding costs at wards, the optimal model is vastly superior to the multi-echelon EOQ. As opposed to the multi-echelon EOQ, the optimal approach is designed as a centralized system used by central pharmacy to control all the inventories. The decision to pursue a global objective at central pharmacy level, rather than at wards level, is due to necessity to collect in short time the information at central level. Another insight of the centralized model is due to the nature of products. In particular, being products perishable products, it is not efficient to collect products in more wards, but it is more efficient to stock them in the central pharmacy and then proceed with products distribution only when a products request appears from a ward.

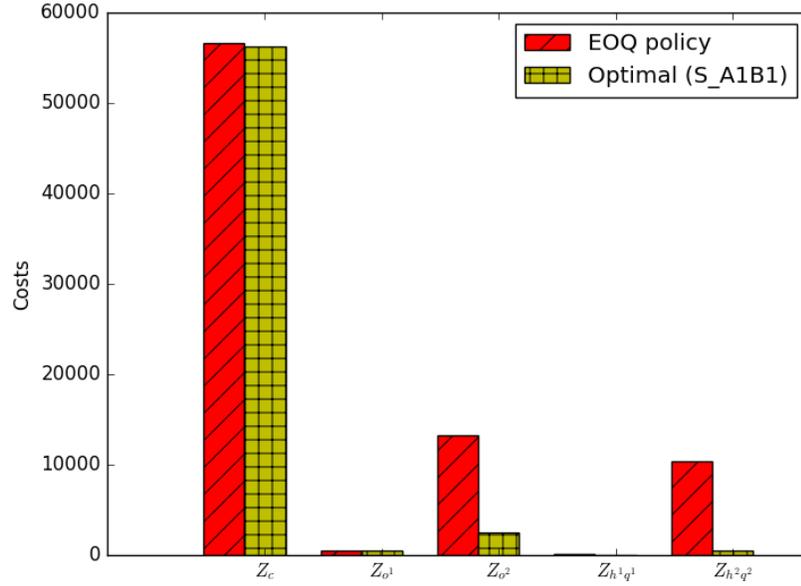


Figure 2: Multi-echelon EOQ policy compared to optimal policy in S\_A1B1 scenario

This point of view is the crucial point to look out for reducing the number of products purchased and wasted due to their expiration date.

Table 1: Comparison of policies

costs	AS IS (Scen_R1)	Multi-layer EOQ	Optimal (S_A1B1)
total cost $Z$	119850.02	80653.47	59695.48
purchase cost $Z_c$ :	91908.16	56569.00	56224.75
total order cost at pharmacy $o^1$	700.00	480	520
total order cost at wards $o^2$	2160.00	13200	2460
total holding cost at pharmacy $h^1$	24144.09	64.38	19.07
total holding cost at wards $h^2$	937.77	10340.08	471.66

### 5.3. product-bundling and sensitivity analysis

Starting from S\_A1B1 as basis, other scenarios have been generated for product-bundling tests and sensitivity analysis. Scenario S\_A1 and S\_A2 are built over the basic scenario in order to investigate variations in holding costs in wards, as shown in Table 2. In order to clarify the effect of bundle aggregation several other scenarios have been generated. While different bundle generation strategies has been designed only for performance testing purpose, the shown scenario reflect a particular bundle generation strategy which consider exactly 2 products aggregated for each bundle. This choice is motivated by the aim of the work to provide as much as possible easy comparable tools with the respect to the as is solution. Bundling should follow the nature of the products (for which some may be aggregated and some not). In the tabled results, the conventional as is solution was named Scen\_R1, and a modified scenario Scen\_R2 considers

high order costs equal to 100 €. These scenarios are compared in Table 3 with the proposed scenarios; Scen\_R1\_B and Scen\_R2\_B, where 30 different bundles of aggregated products are considered and generated heuristically to test the potentiality of the product aggregation with reality. The AS IS solution for Scen\_R1 was obtained by using the historical data of purchased goods from suppliers and to wards and using these data to set the variables  $q_{ist}$ , in the model. The other parameters are equal to the scenario S\_A1B1. The gain remains also when high costs of orders are considered. The sensitivity analysis demonstrated by the graphics in Figure 3, the holding cost results in crucial impact on the system performance as well as the ordering cost obtained by the other experiments.

Table 2: results per scenario

Costs	S_A1	S_A1B1	S_A2
Best total cost $Z$	59,379.74	59,695.74	60,005.38
$h^1$	8.30%	8.30%	8.30%
$h^2$	8.30%	16.60%	33.20%
$o^1$	10	10	10
$o^2$	20	20	20
Mean inventory level for central pharmacy $Q_1$	2.77	5.55	6.97
Mean inventory level at wards $Q_2$	139.81	94.80	51.67

The results clarified a great impact of the feature of bundle aggregation offered by the model. As shown in table 3, the aggregation of products in bundles enable significant reduction in inventory costs at each ward. Those results have great impact for local hospitals management in terms of cost reduction.

Table 3: Results of bundle aggregation (R1\_B and R2\_B) compared with not aggregated ones (R1 and R2)

Costs	R1_B/R1	R2_B/R2
cost ratio $\Delta Z$	99.03%	97.07%
order costs ratio at pharmacy $\Delta o^1$	100.00%	100.00%
order costs ratio at wards $\Delta o^2$	59.50%	59.50%
holding costs ratio at pharmacy $\Delta h^1$	103.06%	103.06%
holding costs ratio at wards $\Delta h^2$	60.98%	100.00%

## 6. Conclusion

Health care logistics optimization is going to be a critical point for health care services because expenditures must be strictly controlled while maintaining high health care service levels. This paper examines the inventory costs optimization when a central hospital pharmacy is responsible for products purchases and logistics to internal wards. The authors developed a multi-echelon heuristics and a mathematical model integrating the different layers of the product distribution systems inside an Italian hospital. The novelties of the proposed approach include the consideration of the aggregation of products in bundles, and the focus on the holding and order cost parameters, estimated by taking into account operational issues of the studied case. The test results shown as the integrated approach could bring substantial improvements to the AS IS

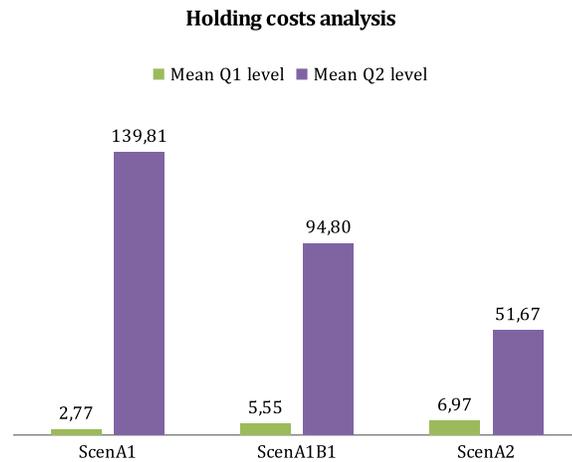


Figure 3: Inventory levels of pharmacy (Q1) and wards (Q2) when holding costs change.

solutions. Moreover, as industrial insight, the analysis underlined the importance of the integration of the operational issue in the inventory cost models, and the requirements for better information sharing policies and for better planning of inventory replenishment policies. The work demonstrated the positive effect of transferring consolidated models and methods from sectors such as discrete manufacturing and supply chain management to service based sectors such as health care service delivery. Through the test run with real data we can conclude that:

- The integrated optimization of all the layers of the product distribution system brings substantial cost savings;
- The labor costs are essential for inventory performance and should be integrated in the inventory model parameters.

Product-bundling as aggregation strategy can be effectively used to find the correct trade-off between the aggregation/disaggregation of products for their purchase/transfer. Other elements that have to be considered in this analysis are the level of safety stock, the degree of products consumption and/or expiration, the effect of economies of scale on the purchase of products from suppliers. In order to offer a complete tool for the decision support system in field of hospitals products management, a set of Key Performance Indicators (KPI) should be considered such as:

- Total cost function including costs of holding, stock, safety stock, purchase, wasting;
- Inventory turnover rate to Central Pharmacy and to single Wards;
- Size of bundles in terms of typology and number of products;
- Length of horizon time for the replenishment planning.

Some of these KPI have been considered in this work, others are in phase of inclusion into the study and will be object of future works. Moreover, future works will better analyze the integration of operation management of personal and cost models to the inventory management

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model. Moreover, for longer time periods (or for more fine aggregated timeslots), and for tests considering higher number of products, sub-optimal or simulation approaches could be considered.

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