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Abstract

Purpose – Logisticians in the worldwide industry are frequently faced with the problem of measuring the total cost of holding inventories with simple and easy-to-use methodologies. The purpose of this paper is to look at the problem, and in particular illustrate the inventory holding cost rate computation, when different kind of warehousing systems are applied.

Design/methodology/approach – A multiple case study analysis is here developed and supported by a methodological framework directly derived from the working group discussions and brainstorming activities. Two different field of application are considered: one related to five companies with manual warehousing systems operating with traditional fork lift trucks; the other is among five companies operating with automated storage/retrieval systems (AS/RS) to store inventories.

Findings – The multi-case study helps to understand how the holding cost parameter is currently computed by industrial managers and how much the difference between manual and automated/automatic warehousing systems impacts on the inventory cost structure definition. The insights from the ten case studies provide evidence that the kind of storage system adopted inside the factory can impact on the holding cost rate computation and permit to derive important considerations.

Practical implications – The final aim of this work is to help industrial engineers and logisticians in correctly understanding the inventory costs involved in their systems and their cost structure. In addition, the multi-case analysis leads to considerations, to be applied in different industrial contexts. As other industrial applications are identified, they may be analyzed by using the presented methodology, and with aid from the data from this paper.

Originality/value – The relevance of this work is to help industrial engineers and logisticians in understanding correctly the inventory costs involved in their logistics systems and their cost structure. In addition, the multi-case analysis lead to interesting final considerations, easily to be applied in different industrial contexts. As other industrial applications are identified, they may be analyzed by using the methodology and extrapolating the data from this paper.

Keywords Inventory management, Total cost, Warehousing

Paper type Case study

1. Introduction

Knowledge of holding costs constitutes a vital part of any industrial logistics systems management, as they are widely used in well-established inventory management models such as Economic Batch Quantity (i.e. Harris, 1990; Wilson, 1934), Joint Economic Lot Size Analysis (Hill, 1997; Goyal, 2000) and in all recent studies where an inventory model is developed and an inventory holding cost needs to be computed (i.e. Choi and Noble, 2000; Thiagarajan and Rajendranz, 2003; Persona *et al.*, 2007;

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Battini *et al.*, 2009, 2010). Generally speaking, any industrial system has the need to compile solid inventory cost parameters in order to drive logisticians decision making, both for logistics and management purposes (Daugherty *et al.*, 2011; Defee *et al.*, 2010; Randall *et al.*, 2011). This work focusses on total inventory carrying cost computation, which is a relevant factor in several situations, i.e. in warehouse investment decisions and in any situation in which efficient inventory management becomes a priority (i.e. the centralized/decentralized control of inventories, Bregman *et al.*, 1989; Cattani *et al.*, 2011).

An intuitive choice of this index could lead to misunderstanding and errors in the inventory management models application. As recently underlined by Berling (2008) it is surprising that "little effort has been put into finding ways for accurately determining the cost parameters used for inventory control, i.e. the holding cost rate although such costs are used as inputs in nearly all existing methods and heuristics." Traditionally, it is a common assumption that the holding cost parameter is a constant and is expressed as a percentage of the product value. This approach is based on the assumption that capital cost makes up most of the cost (Singhal and Raturi, 1990; Berling, 2008). Decades of research are summed up in several studies (Plossl, 1967/1985), yet it is still difficult to find detailed results of efficient applications in industrial contexts, able to guide managers in the correct determination of the holding cost rate. Existing literature offers only general guidelines: textbooks published in 1990 report widely that, while the carrying costs will vary with specific situations, they can be estimated at 20-50 percent above the inventory value (e.g. Schonberger and Knod, 1997; Pyke and Cohen, 1994), while Stock and Lambert (1993) suggests a value ranging between 12 and 34 percent and closes the range with a 18 to 25 percent above inventory value, depending on the industrial field; and Clendenen and Rinks (1996) assume an holding cost equal to the 30 percent of the product cost in their pull inventory model. Consequently, holding costs are often not precisely known and usually approximated by managers, according to different rules of thumb depending on the industry.

Among both inventory theorists and practitioners, it is common practice to include in the holding cost rate an opportunity cost rate by applying the discounted cash flow approach (Grubbstrom, 1980). Such approach allows roughly incorporated the cost of capital in an average cost (AC) inventory model. This AC approach in single source models with only forward logistics is straightforward and usually produces good results (Teunter *et al.*, 2000), thus, the opportunity cost of inventory investment are usually included in the traditional holding cost parameter computation model. It is important to recognize that inventory costs extend well beyond the capital cost of materials, including both evident and hidden costs, which means out-of-pocket holding costs (Schonberger and Knod, 1997). In a recent study, Berling and Rosling (2005) show that the capital cost of goods varies considerably due to the effect of different financial risks on inventory policy. Berling and Rosling (2005) suggests a computation method based on an activity-based costing concept, where cost drivers are the amount of activity used to store one unit of product. Only in few of these studies, the holding cost is assumed to be variable over time: Giri *et al.* (1996) developed an Economic Order Quantity (EOQ) model in which the holding cost is a continuous function of time, while Goh's (1992) model provides holding cost variations expressed as non-linear functions of storage time or level; VujoBevi *et al.* (1996) handle imprecise holding cost parameters in EOQ inventory model by using fuzzy sets; and Beltran and Krass (2002) analyze the dynamic lot sizing problem considering concave holding costs. Corbacẏoglu *et al.* (2007)

discuss complications in finding the correct holding cost parameters in case of joint manufacturing and re-manufacturing, demonstrating the limits of the traditional evaluation methodology. Alfares (2007) considers storage-time dependent holding cost, where cost is an increasing function of the time spent in storage. This approach is definitely suitable in case of deteriorating and perishable items such as food, but might not necessarily work in different situations.

In conclusion, a widely accepted methodology for determining holding costs has yet to be established, even if the traditional AC approach is still the most used and applied both in literature and in practice (Teunter *et al.*, 2000).

2. Problem definition and scope

Existing literature has extensively covered many aspects of warehouse activities, but in the last few years, emphasis has been put on automation of all logistic aspects including warehouse activities (i.e. the diffused use of self-cladding automated storage/retrieval system (AS/RS) warehouses or modular storage systems). As warehouse activities get progressively more automated, the need for specific guidelines to measure holding costs becomes more urgent. Automated warehouses represent a very different reality from traditional manual or semi-automated warehouses, where costs are mostly linked to labor and other variable costs.

The aim of this work is to present a multiple case study to explore the cost variables included in the inventory carrying cost computation in various contextual settings, and derive useful suggestions and considerations for practical application. In this work, ten different Italian SMEs (located in the north-east part of the country) are directly studied in order to define all costs associated to inventories and measure total inventory carrying costs. The ten cases are grouped into two different sets: one made of five companies with manual warehousing systems, operating with traditional fork lift trucks; the other consists of five companies operating with highly automated warehousing. The multi-case analysis is performed by the authors in collaboration with a panel of ten operation managers and ten logisticians in order to stress the difference between manual and automatic/automated warehousing systems and defining all estimated costs.

These pages present a unique collection of inventory cost parameters that should widen the available reference material, in order to improve overall understanding of holding costs, and should serve as a guideline for managers to determine a correct value of their inventory holding cost rate. As other industrial applications are identified, they may be analyzed by using the methodology presented and thanks to the data from this paper.

The first part of this study consists of the presentation of the methodology applied, with a detailed consideration of all costs; then, ten case studies (from different sectors and characterized by homogeneous storage facilities) are presented. Once all the data are gathered, two analysis are presented: one regarding the holding cost parameter in case of traditional and manual storage systems and one regarding the computation of the holding cost rate in automated warehouses, finally conclusions are drawn concerning the range of existing holding costs and their computation.

3. Methodology

The operation managers and executives solicited by the authors for this multi-case analysis, were intentionally subdivided in two different working groups: the five companies operating with traditional manual warehousing systems in one group, and the five companies with highly automated warehousing environments in the second group. The selection of the ten companies was determined to provide a consistent set of successful Italian SMEs of different age and size (from 50 or more employees to one with nearly 250 employees), pursuing different products and located in different parts of the country; operating in ten different sectors, including technologies in the areas of professional kitchens, lather tannery, electronics compliances, ignition devices and food and beverage. In addition, their presence on the market also spread from a more than 50-year-old company founded in 1960, to a very "new" company founded in 2002 and already realizing significant revenue. A variety in number of employees is also well represented, including small companies with only about a dozen employees, as well as several companies with 70 or more employees, and one with nearly 150 employees.

The operation managers and executives involved by the authors in the multi-case analysis were involved in a brainstorming session meant to identify the most important influencing variables due to measure the total cost of holding inventories. Ten participants were involved, one for each company engaged in the study. The group turned out to be pretty heterogeneous in terms of age, experience and length of service (it is not possible to say the same think about gender, since just a woman was involved in the study). The session was lead by a facilitator, which is one of the author; other two authors played a secretary role, grabbing and writing down ideas and opinions coming out along the session. Some simple ground rules were established before running the brainstorming:

- portable phones, computers or any personal devices were not allowed in the room;
- a portable fork lift truck was used as changeover: only the person with the truck in his hand was allowed to talk;
- criticism as well as expressions like "no," "I don't think so," "I disagree," etc. were banished.

The session lasted about three hours; after the presentation of the research question and a quick icebreaker activity where each participant was asked to state which was the funniest thing about his job, the facilitator invited the group to list the most important influencing variables due to measure the total cost of holding inventories. This activity really helped to explore manager's "mental models" of the inventory cost structure according to their future aims and needs. After a couple of hours of session, the brainstorming moderator encouraged the participants to find a way to refine and narrow the list which was created due to group ideas together and to capture the main themes that were discussed. From this process it was obvious the identification of two different perception of cost structure for manual and automatic warehousing. Thus, results of the brainstorming session were used by two different working groups: the first related to the five companies operating with traditional manual warehousing systems and the second one related with highly automated warehousing environments.

The two working groups finally agreed on two different evaluation approaches according to the specific warehousing context in which inventory are stored by the companies involved. The framework illustrated in Figure 1 shows the essence of the methodology applied in this multi-case analysis, based on the assumption that the appropriate computation model should be dependent on the kind of warehouse adopted in each individual plant and on the management mission and future needs. Therefore, different warehousing systems within the same plant should lead inventory managers

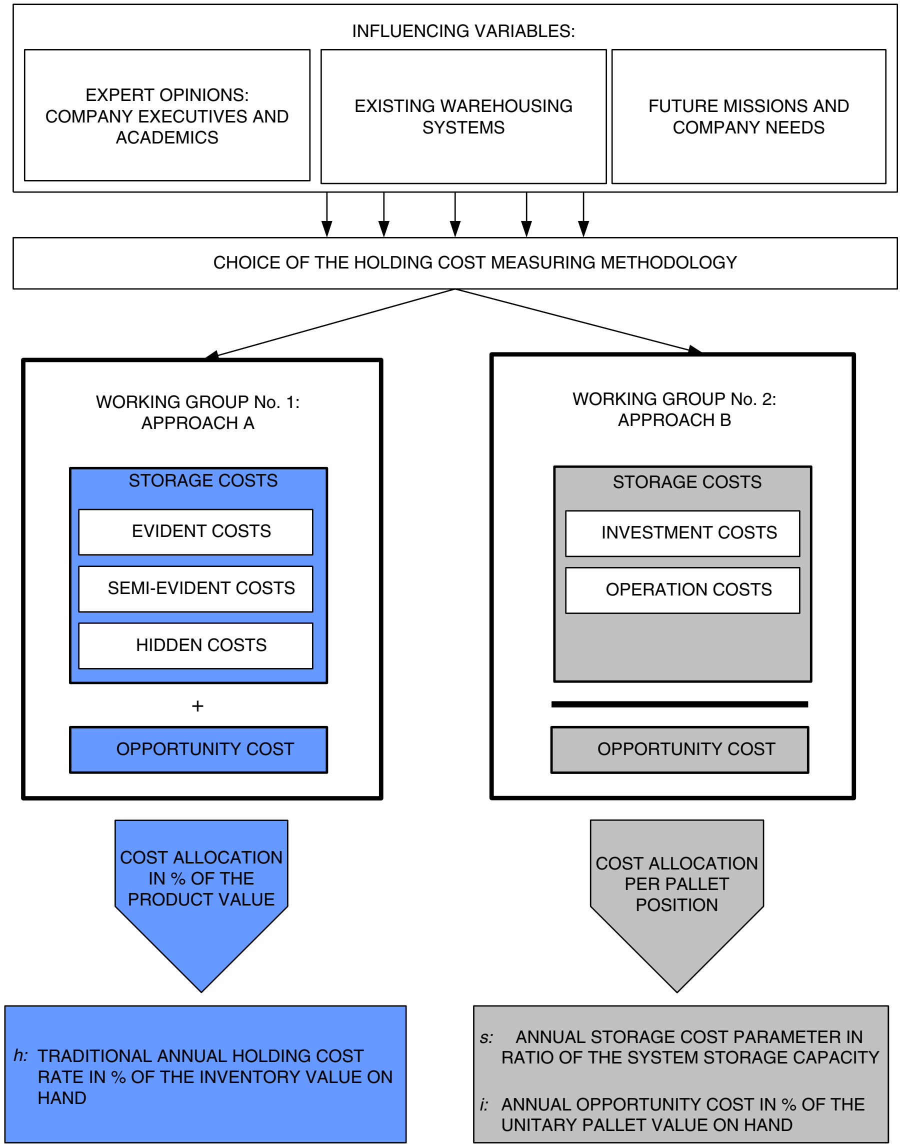

Figure 1.
Structure of the holding cost measuring methodology applied in the multi-case analysis, as defined by the two working groups involved in the empirical study

toward different and specific inventory holding cost rates following the most cost-effective solution for that specific warehouse. According to the study of Van den Berg and Zijm (1999) a "warehousing system refers to the combination of equipment and operating policies used in an item picking or storage/retrieval environment." Three kinds of influencing variables have been taken into account during the group discussions:

(1) The expert opinion on inventory cost computation and cost structures which consist mainly of three items: initial investment on a warehousing system (the

building construction/rent, the site preparation, purchase, installation and integration of equipment infrastructure and information technology architecture), system operating costs, directly linked to all daily warehousing activities and financial risk related to the monetary value immobilized by the company in all stored products/materials/semi-finished parts. The financial risk on inventories is primarily connected with capital opportunity costs of the products stored.

(2) The warehousing system in use in the company. According to Van den Berg and Zijm (1999), three kinds of warehousing systems can be identified inside a manufacturing plant: manual warehousing; automated warehousing and automatic warehousing. Given the right circumstances, manual warehousing systems, in which the order picker is an operator aboard industrial trucks (fork lift trucks, reach-trucks) or other kinds of vehicle (i.e. pick carts, container carts, etc.) along pick locations (Van den Berg and Zijm, 1999), are still a justifiable solution to many storage applications today. In automated warehousing systems, computer-controlled equipment is used for storage and selection of different products (i.e. a carousel system). The AS/RS in both its forms, whether "highly automated storage system" or "miniload AS/RS," designed for the storage and handling of small items stored in modular storage drawers/bins (Van den Berg and Zijm, 1999), are included in this type of systems. Finally, if the order picker is replaced by a carousel system or rotary rack operated by a robot, an "automatic order-picking system" is created, like the A-frame automatic dispenser machine employed in the pharmaceutical industry (Van den Berg and Zijm, 1999). Anyway, the difference between "automated," "fully-automated" and "automatic" warehousing systems is traditionally rather thin. In this work, the analysis is focussed on the manual warehousing typology and on the AS/RS warehousing systems (belonging to the fully-automated family), highly diffused in the worldwide industrial sector. The automatic warehousing systems (performing high-speed picking of small- or medium-sized non-fragile items of uniform size and shape) are not considered in this field study, since they are specific to few sectors such as electronics and pharmaceutical (according to Van den Berg and Zijm, 1999). Moreover, it could be easily re-conducted to the automated one without great difficulties.

(3) The future mission of the company and operation managers' needs.

Once these three aspects are analyzed and once the kind of warehousing used is determined, it is time to identify the most appropriate measuring approach for each individual case, whether the group decided to apply the most traditional approach (Approach A) consisting in the computation of an average inventory holding cost parameter h as a percentage of the stored product value, including the opportunity cost value, chosen by group one; or developed a different cost subdivision (Approach B), consisting of the computation of an average inventory storage cost parameter s expressed as a function of the total number of pallet positions available in the warehouse (or other specific stock keeping unit (SKUs)), without including the opportunity cost value, chosen by group two.

The parameter in this case is made up of two components: an investment cost per storage location and an operational cost per storage location, in both cases parameters are calculated per time unit of one year, which is not necessary for our purpose.

The subdivision of the computation methodology into two different approaches derives from the assumption that different levels of warehousing automation cause different costs ratio. The level of automation has, in fact, a direct impact on the fixed storage costs of a warehousing system (Roodbergen and Vis, 2009).

Approach A is suitable and preferred when the level of fixed and variable storage costs is approximately the same, while Approach B is better suited when the main part of total annual carrying costs is represented by fixed costs. In traditional and manual environments, fixed costs are usually less significant, but they become the main portion of the expense, in automated and automatic systems. Table I shows in detail the two storage cost structures introduced in Figure 1. The total storage cost together with the opportunity cost (the cost of the capital invested in inventory), provide the total holding cost value (Figure 1). The two groups defined and carefully calculated each all the different costs: 20 different items for group A, and 16 different items for group B. Rather than being considered completely different methodologies, the two approaches simply provide a different emphasis on the case studies analysis and on the management perspective.

3.1 Approach A

According to the measuring Approach A, the cost structure is subdivided in three parts: evident costs, semi-evident costs and hidden costs, following the guidelines suggested by Schonberger and Knod (1997). In manual warehouses, only a part of the total inventory costs are easily quantifiable, and most of them are sunk and hidden in other costs, not directly attributable to inventories. In several manual warehousing systems, semi-evident and hidden costs play a relevant role in estimating the global costs and for this reason they must be accurately estimated and correctly allocated to

Cost structure A	Cost structure B
Evident costs	*Investment costs*
1. Floor space	1. Machines
2. Energy	2. Racks
3. Cleaning	3. Control system
4. Surveillance	4. Fire protection
5. Insurances	5. Aisle equipment
6. Taxes	6. WHMS and HAS equipments (HW and SW)
7. Material handling/storage equipments	7. Installation and testing
8. WHMS and HAS equipments	8. Training
9. Maintenance	9. Conveyor systems
10. Direct labor	10. Lands and building
Semi-evident costs	*Operation costs*
1. Obsolescence	1. Indirect labor
2. Product damage	2. Supervision
3. Product depreciation	3. Energy
4. Product deterioration/expiration	4. Maintenance
5. Indirect labor and supervision	5. Product damage/depreciation and deterioration
6. Stock list execution	6. Lost sales or backlog
Hidden costs	
1. Inspection and counting during the year	
2. Remanufacturing	
3. Repackaging and relabelling	
4. Lost sales or backlog	

Table I.
Storage cost structures as defined by the two study groups

the storage system. For example, obsolescence risk needs to be considered (most significant for technology-based companies, where the risk that a process, product or technology used or produced will become obsolete and no longer competitive in the marketplace), and capital invested in obsolete stored products cannot be recouped and a re-manufacturing process is required. Lee and Billington (1992) highlight that re-manufacturing of stored items and risk of obsolescence might alone increase inventory costs of about 40 percent. Otherwise, when high market price fluctuation needs to be considered (i.e. falling price of steel and higher raw material costs), capital invested in inventories can be strongly affected, making evident costs marginal. According to cost due to product damage are relevant in traditional manual environment in which the human factor needs to be considered, on the contrary, product damage is strongly reduced in automated and automatic warehousing systems. In case of products that are subject to a significant deterioration (i.e. fresh food products), completely deteriorated items are discarded and partially deteriorated items are offered at discounted priced, with inevitable effects on the capital invested in inventories. As a consequence, in several traditional storage systems the necessity of re-manufacturing, repackaging and relabeling materials becomes indispensible, and SKU operations arise, increasing the hidden portion of inventory costs. "Hidden costs" are considered all inventory costs that blend with other costs and are difficult to recognize, yet must be considered and estimated with a certain margin of accuracy. One common example of hidden cost, is item disappearance, particularly in manual environments, which require numerous inspections and counting throughout the year.

For the reasons explained above, study group A assumed that a relevant part of semi-evident and hidden costs considered in their approach, are approximately linear in the capital invested. Supported by this assumption and according to the traditional approach, the group set all estimated costs as percentages of the mean inventory investment value registered during the year under study. Then, the opportunity cost of inventory investment is finally added in order to obtain the holding cost parameter computation, expressed as a percentage of the unitary product value on hand.

3.2 Approach B

In comparison with manual warehousing, automated warehousing provides several advantages, like the elimination of machine operators, reduction in floor space utilization, and higher return on investment, without taking into account, reduced training times, higher inventory security and less product damage. For further insight on this topic see Van den Berg and Zijm (1999), Roodbergen and Vis (2009) and Azzi *et al.* (2011). In automated and automatic warehousing systems operational costs are additionally reduced with the introduction of standard PC-based supervisory control, which provides higher accuracy than bar code systems usually adopted in manual environments, while a well-integrated Warehouse Management System Software (WHMS), reduces product deterioration and its connected expenses.

For these reasons, study group B developed a measuring approach based on capacity cost elements, starting with the initial capital investments necessary to provide a certain level of storage capacity in the system. Their cost structure is subdivided only into two parts: investment and operating costs. Capacity costs reflect the total amount of storage capacity purchased (and not always utilized) in the medium-long period, and cannot be modified during the year. As a result, in Approach B, the total storage costs are expressed as a ratio of the storage capacity of the systems (in other words, the number of pallet positions/SKUs available in the medium-long term). In this case, the group decided to not include obsolescence costs and opportunity costs of inventories: obsolescence costs have been approximated to zero under the assumption of a higher inventory turnover, while the opportunity costs should be calculated in the same way as for the Approach A and expressed as a percentage of the pallet/unit value stored in the warehouse, but are not directly added to the storage cost portion, but kept disjointedly as illustrated in the scheme reported in Figure 1.

3.3 Different emphasis for different objectives

Empirical evidence confirms that the way companies quantify inventory carrying cost has a deep effect on how correctly they perform inventory choices. Expressing holding cost in percentage of the product value is helpful in manual warehousing systems because it encourages inventory reduction. In fact, in warehousing systems with low fixed storage costs a reduction in inventory quantities not only leads to a reduction of opportunity costs, operational costs (storage/retrieval) and handling costs (clearly, in a smaller warehouse, the travel times for order-handling are smaller), but, it also opens the possibility of warehouses equipments reconfiguration with a consequent reduction of floor storage, and increased room for production activities. On the other hand, in automatic and automated warehousing systems a flexible reconfiguration and redesign of the system is impossible because equipments are dimensioned in the medium-long period. Thus, once the warehouse has been well dimensioned the best option is to saturate the nominal storage capacity (Roodbergen and Vis, 2009), allowing a higher return on investment. Under these considerations, keeping the opportunity cost value separated from storage cost index expressed as a ratio of the real warehouse storage capacity, will encourage system capacity saturation.

In conclusion, the two methodologies applied in this empirical study lead to measuring two kind of inventory carrying cost parameters, which, rather than being different in the substance, reflect a different emphasis (as showed by the two working groups) on inventory costs analysis and warehousing systems management.

4. Empirical results

The first group of companies, Italian leaders in five different manufacturing sectors, raw materials, semi-finished part and finished product inventories are stored in traditional single-depth-pallet-racking warehouses, with operators conducted aboard fork lift trucks. The five cases can be compared, from a logistic point of view, since they use the same kind of warehouse, storing SKUs of homogeneous weight and structure dimensions with a height ranging from five to eight meters.

The second group concerns a set of five companies that have recently invested considerable capitals in really similar AS/RS warehousing systems, with different storage capacity, even if they are of different dimensions and sector of operation (belonging to manufacturing and food/beverage sectors). In addition, they all use self-supporting warehousing systems with double deep pallet rack shelving.

As mentioned in Section 1, a comprehensive collection of industrial inventory costs data and inventory holding cost parameter is still lacking, and very few researches concerning this issue can be found in literature. For this reason, the authors conducted a full computation of all inventory costs, including a final value for inventory holding cost parameters in each single case study. Quantitative data were extrapolated from the ERP and the WHMS software systems, while a series of one-to-one discussions, in-depth interviews and work-groups with key operators (warehouse managers, trucks operators, planners and controllers, etc.) and other professionals allowed a satisfying collection of non-quantitative data and a close estimation of semi-evident and hidden costs (as defined in Table I). Inventory costs and final results are displayed in Table II: inventory holding costs are obtained as the sum of all costs reported in the table (including opportunity costs), and are all expressed in percent of the mean inventory investment. Table III provides an example of how each cost has been measured for the first company (case study A in Table II). Table IV displays all storage costs for the second group of industries, following the cost structure defined in the methodological framework (Section 2). Here, annual and monthly storage cost are expressed in € per pallet position, and are obtained adding yearly annual equipments amortization, annual building amortization and all annual operation costs; the total value is expressed as the ratio of the AS/RS warehousing system total storage capacity. Mean unit costs data (evidenced in gray in Table IV) of an AS/RS machine, racks, aisle equipments, WHMS and HAS software systems and of the total investment are also derived by the five case studies analysis.

The cost data collected and displayed in Tables II-IV and the methodology employed in this field study require some further clarifications:

(1) All costs displayed in Tables II-IV refer to the year 2008 and are expressed in Euro.

(2) Opportunity cost value reported for case studies A-B-C-D-E in Table II have been estimated according to company's management indications and expressed as a percentage of the unitary product value on hand. Opportunity cost represents the cost of capital for inventory investment, which is the rate of return capital providers would expect to receive if they would invest their capital elsewhere. Only the opportunity cost used in case company D (equal to 5.15 percent in Table I) reflects entirely the value of company debt finance in the year analyzed.

(3) The annual equipments amortization schedule (in Table III) used for this study is provided by the official Italian regulation for each specific industrial sector studied. According to such regulation, it becomes possible to consider the warehousing system as a whole, comprehensive industrial unit even if AS/RS systems might be made up of different parts, with an annual percentage of amortization of 17.5 percent. On the other hand, industrial buildings' amortization rate is calculated with a 3 percent index.

(4) "Lost sales or backlog" costs arise any time a warehouse portion or a machine is not operating properly due to equipments failures. All companies analyzed in this work were unable to provide clear information on this cost, which forced the study to completely exclude this variable from the computation even if all managers agreed that downtime costs can easily reach two points percentage of the mean inventory investment present in the warehousing system.

5. Results discussion

5.1 Inventory holding costs computation in case of manual warehousing systems

One of the first issues to assess for group A, was the complete quantification of all inventory costs for each case, without omitting semi-evident and hidden costs, to understand how these companies cope with inventory issues in their storage system, and how each solution can affect the final value of the inventory holding cost parameter.

Table II.
Results for study group 1

Industrial case	Case A	Case B	Case C	Case D	Case E
Industrial sector	Professional kitchens	Leather tannery	Electric engines	Electronic products	Ignition devices
Racks type	Single deep pallet racking operated with traditional fork lift trucks				
Warehouse height	From 5 to 8 meters				
Maximum pallet weight (kg)	2,000	1,500	1,500	1,800	2,000
Mean inventory investment (€)	6,031,667	4,718,954	3,800,000	5,769,550	5,904,920
Evident costs (% of the mean inventory investment on hand)					
1. Floor space	3.44	2.54	0.00	5.58	0.47
2. Energy and services	1.51	0.42	0.09	0.69	0.08
3. Cleaning	1.19	0.34	0.01	0.40	0.02
4. Surveillance	0.66	0.42	0.00	0.83	0.00
5. Insurances	0.18	0.25	0.06	0.21	0.02
6. Taxes	1.35	1.02	0.61	0.98	0.51
7. Material handling/storage equipments	4.27	2.54	2.39	4.23	1.52
8. WHMS and HAS equipments (HW and SW)	0.12	0.64	0.00	0.18	0.12
9. Maintenance	0.03	0.00	0.00	0.01	0.02
10. Direct labor	1.82	0.64	0.29	2.27	1.77
Total	14.56	8.82	3.44	15.38	4.53
Semi-evident costs (% of the mean inventory investment on hand)					
1. Obsolescence	2.04	0.32	6.84	6.89	5.16
2. Product damage	0.01	0.00	0.03	0.21	0.00
3. Product depreciation	0.47	0.09	0.56	2.43	0.00
4. Product deterioration/expiration	0.17	0.74	0.00	0.00	1.39
5. Indirect labor and supervision	0.83	1.59	0.79	0.66	1.65
6. Stock list execution	0.18	0.31	0.22	0.26	0.09

(*continued*)

Table II.

Industrial case	Case A	Case B	Case C	Case D	Case E
Total	3.70	3.05	8.45	10.45	8.29
Hidden costs (% of the mean inventory investment on hand)					
1. Inspection and counting during the year	0.18	0.31	0.22	0.26	0.17
2. Remanufacturing	0.05	3.18	0.66	0.00	0.00
3. Repackaging and relabeling	0.00	0.00	0.00	1.73	0.00
4. Lost sales or backlog	–	–	–	–	–
Total	0.23	3.49	0.88	1.99	0.17
Total annual storage costs (€/year)	1,115,349	724,428	485,209	1,605,008	767,049
Annual opportunity cost	7.00	7.00	10.00	5.15	9.00
Inventory holding cost parameter h	25.49	22.35	22.77	32.97	21.99

Note: Inventory holding cost components (expressed in percent of the mean inventory investment on hand) and total holding cost parameter in the five different case studies operating with manual warehousing systems

Industrial case	Case A		
Industrial sector	Modular professional kitchens: raw materials, semifinished and finished products		
Racks type	Single deep pallet racking operated with fork lift trucks		
Warehouse height	5 meters		
Floor space occupied by inventory	16,320 square meters		
Mean inventory investment (€)	6,031,667		
	% of mean inventory investment	Notes of computation	Costs allocation
Evident costs			
1. Floor space	3.44	Annual building ammortization charge	Floor space for inventory: 16,320 square meters
2. Energy	1.51	Annual expense for heat, light, power	Floor space for inventory: 16,320 square meters
3. Cleaning	1.19	Annual cleaning service cost	Floor space for inventory: 16,320 square meters
4. Surveillance	0.66	Annual surveillance service cost	Floor space for inventory: 16,320 square meters
5. Insurances	0.18	Annual building and equipments insurance rates	Floor space for inventory: 16,320 square meters
6. Taxes	1.35	Building and land annual taxes	Floor space for inventory: 16,320 square meters
7. Material handling/storage equipments	4.27	Annual equipments ammortization charge (racks, fork lift trucks, etc.)	All
8. WHMS and HAS equipments (HW and SW)	0.12	Annual equipments and software licences ammortization charge	All
9. Maintenance	0.03	Hours of maintenance recorded by personnel: 40 hours during the year	All
10. Direct labor	1.82	Trucks operators: 5 per day	All

(continued)

Table III. Example of inventory holding cost components computation: case study A

Table III.

Industrial case		Case A	
Semi-evident costs			
1. Obsolescence	2.04	Value of obsolete products removed from warehouse due to technical changes and re-engineering	All
2. Product damage	0.01	Total value of products damaged due to human errors recorded by personnel	Estimated quantity: 10% of all
3. Product depreciation	0.47	Fall in price of steel raw materials on the 31 December 2008	All
4. Product deterioration/expiration	0.17	Total value of products discarded during the year	Estimated quantity: 10% of all
5. Indirect labor and supervision	0.83	Scheduling, control, supervision and training: 2 persons involved	% of time: 60% of each person
6. Stock list execution	0.18	2 working days with 30 persons involved per day	All
Hidden costs			
1. Inspection and counting during the year	0.18	Equal to a second stock list execution during the year	All
2. Remanufacturing	0.05	Production costs of remanufacturing work orders recorded during the year	Estimated quantity: 10% of all
3. Repackaging and Relabeling	0.00	None	–
4. Lost sales or backlog	–	Not quantifiable	–
Annual opportunity cost	7.00		
Inventory holding cost parameter h	25.49		

Table IV. Results for study group 2

	Case F	Case G	Case H	Case I	Case J		
Industrial case							
Industrial sector	Mechanical parts	Office Furnitures	Fasteners	Fresh products	Beverage		
Storage capacity (pallet positions)	9,940	13,050	20,700	50,500	80,000		
Total pallets moved/hour	95	120	180	330	120		
Maximum pallet weight (kg)	1,100	1,200	1,500	1,000	1,500		
Racks type	Double deep high bay racks operated with automatic rack servicing cranes						
Building type	Rack clad building						
Warehouse height (m)	20	26.7	30	28.4	29		
Aisles	4	4	6	9	16		
AS/RS machines installed	4	4	6	9	4		
Investment costs (€)							
1. AS/RS machines installed	1,160,000	1,180,000	1,620,000	2,880,000	1.180.000	Mean unit costs	Unit of measure
2. Racks installed	781,000	1,070,000	1,760,000	4,974,000	8.453,000	294,000	€/machine
3. Control system	140.000	153,000	200,000	245,000	289.000	90	€/pallet position
4. Fire protection	335,000	238,000	265,000	235,000	248000		
5. Aisle equipments	240,000	280,000	480,000	630,000	1.152.000	72,400	€/aisle
6. WHMS and has system (HW and SW)	85,000	45,000	80,000	85,000	100,000	79,000	€/system
7. Installation and testing	20,000	32,000	30,000	50,000	45,000		
8. Training	35,000	30,000	35,000	30,000	35,000		
9. Conveyor system	150,000	230,000	265,000	550,000	265,000		
Total equipments	2,946,000	3,437,000	5,001,000	9,679,000	11,767,000		
10. Land and building	1,350,000	2,153,000	2,188,000	7,029,000	12,475,000		
Total investment	4,296,000	5,590,000	7,189,000	16,708,000	24,242,000		
Total .investment/pallet position	432	428	347	331	303	368	€/pallet position
Annual equipments amortization (17.5%)	515,550	601,475	875,175	1,693,825	2.059,225		
Annual building amortization (3%)	40,500	64,590	65,640	210,870	374250		

(*continued*)

Table IV.

	Case F	Case G	Case H	Case I	Case J		
Operation costs (€/year)							
1. Labor indirect	41,000	10,000	20,000	36,000	70.000		
2. Supervision	6,000	6,000	7.000	35,000	45,000		
3. Heat, light, power	78,000	63,000	72,000	112,000	135,000		
4. Maintenance	17,000	12,000	15,000	35,000	45,000		
5. Product damage	6,000	10,000	30,000	58,000	54.000		
6. Lost sales or backlog	–	–	–	–	–		
Total annual investment costs (€/pallet position)	55.9	51.0	45.5	37.7	30.4	44.1	€/pallet position
Total annual operation costs (€/pallet position)	14.9	7.7	7.0	5.5	4.4	7.9	€/pallet position
Inventory storage cost parameter *s*	70.8	58.8	52.4	43.2	34.8	52.0	€/pallet position/ year
Inventory storage cost parameter *s*	5.9	4.9	4.4	3.6	2.9	4.3	€/pallet position/ month

Notes: Inventory storage costs in the five different case studies operating with self-supporting AS/RS warehousing systems. The ten investment cost refer to initial investments (year 2007), while the operation cost are quantified for one year of operation (year 2008)

The first company analyzed (case A in Tables II and III) concentrates its production on catering equipment for domestic and international markets. The study is focussed on the total amount of raw material, semi-finished products and finished product inventories stocked in one of the three facilities of the company. Continuous improvements in product performances, to adapt to market demand, increase considerably the risk of obsolescence of stocked materials and semi-finished products, which cannot be easily modified and re-manufactured. Thus, obsolesce costs reach 2.04 percent of the mean inventory investment in 2008.

The second company (case B in Table II), specialized in the production of leathers for furnishing, clothing and upholstery, with six manufacturing plants in Italy and a total production of about five million square meters of leather per year. Their warehouses store high quantities of raw material and chemical additives (used for its processing). In this case the monetary value of semi-finished product inventories is high, technical obsolescence is low and obsolescence costs are contained, thanks to re-manufacturing processes by which stocked materials can be transformed to meet customers' needs. This can create unexpected hidden costs (the 3.18 percent) caused by the re-manufacturing processes and semi-evident costs due to the indirect labor required (1.59 percent).

Case study C concerns an electromechanical company producing customized versions of induction motors for special applications, with a production of 200,000 motors per year. Due to the high technical evolution of the sector, the company is characterized by high risk of obsolescence (6.84 percent), particularly for assembly parts and pre-assembled components (Table II).

Case study D takes into consideration holding costs of a big company which designs, produces and supplies electronic products of large consumption. The majority of the products is designed in Italy and imported from the Far East, which creates long procurement lead times. Finished product inventories are particularly exposed to high depreciation risk (2.43 percent) and technical obsolescence (6.89 percent). For example, a DivX reader can precisely depreciate of 50 percent in only one year.

Finally case study E involves an Italian manufacturer of components for heating systems, which in the last ten years achieved the absolute leadership on the national market. The company is significantly involved in the technological development of their products for private and industrial applications by continuous testing, modification and improvements of heating devices according to customers' applications. Thus, obsolesce costs of inventories reached 5.16 percent in 2008, while deterioration costs of stored components 1.39 percent of the mean inventory investment (Table II).

In summary, the following remarks from the first empirical analysis focussed on manual warehousing systems (working group No. 1):

(1) *Inventory holding cost parameters range between a minimum of 21.9 and a maximum of 32.9* percent *of the inventory value on hand.* Although the high difference between the five case studies, the final inventory holding cost parameters range between a minimum of 21.9 percent (case E) to a maximum of 32.9 percent (case D) of the inventory value on hand. Considering that lost sales and backlog are not quantified in this analysis (as explained in Section 4) and that some semi-evident and hidden costs could be underestimated due to lack of data, we must assert that holding cost parameters are at close to 25 percent of the inventory value on hand, and sometimes (case E) even ten points more. Thus, our results confirm existing literature findings on the

subject, and suggest that 25 percent is the minimum reasonable value that can be used as rule of thumb to try and estimate inventory holding costs.

(2) *It seems almost impossible to reach standard percentage ranges for each cost.* Holding costs should not always be based on industry averages, but calculated case by case in accordance with specific business and warehousing system. Every cost is highly dependent on the industrial sector of operation, in addition to being dependent on the warehousing system in place. This said, it seems almost impossible to reach set percentage ranges for each cost as attempted by Richardson (1995).

(3) *Semi-evident and hidden costs are equal or even higher than evident costs.* From our experience, it is reasonable to state that semi-evident and hidden costs can be equal (case B and D), and even higher (case C and E) than evident costs, hence they can become a relevant variable in the inventory cost parameters. Only in case study A evident costs represent more than three times the semi-evident and hidden costs. In addition, in any of the cases studied, the opportunity cost of capital represent the leading factor in determining the percentage of carrying cost, but each cost defined in the methodological framework needs to be carefully figured out. This process requires a full comprehension of the industrial sector of operation and a deep analysis of inventory carrying problems existing within the company. Nowadays, warehousing management systems (like WHMS software systems) are still much focussed on evident storage costs computation and detection (in particular on automated machine and manpower costs involved in picking and handling operations), and are unable to fully understand the impact of hidden costs.

5.2 Inventory holding costs computation in case of automated warehousing systems

The five different companies with automated warehousing systems all have recently invested in double-depth bay racks warehousing systems with automatic rack service cranes (also called AS/RS systems). All case studies use pallet racking as supporting elements for roof and wall (rack-clad buildings) and the maximum pallet weight considered is 1,500 kg/pallet.

Table IV reports all data collected and the inventory holding costs are quantified according to the methodological framework proposed in Figure 1. The cost structure is now different from the previous one: it is divided in investment costs and operation costs. All investment costs defined in the methodological framework are precisely quantified and carefully allocated using the two amortization rates reported in the table and discussed in paragraph 4, while operation costs are expressed for one year of operation.

In summary, the following remarks stem out of this second empirical analysis focussed on AS/RS warehousing systems (working group No. 2):

(1) *The annual storage cost parameter ranges between 34.8€ and 70.8€ per pallet position as inverse function of the warehouse storage capacity.* As it can be seen from Table IV, the annual storage cost parameter s varies between 34.8€ and 70.8€ per pallet position available in the warehouse, which means a monthly cost between 2.9 € and 5.9 € per pallet position. Data collected in Table IV show that the storage cost parameter decreases (from case study F to case study J) as the AS/RS storage capacity increases. This evidence confirms the theory that in case of an AS/RS warehousing system, holding costs are mainly made up of capacity

costs rather than product value or kinematics performance of the AS/RS machines, and supports the choice of keeping the s parameter separated from the opportunity cost of the capital invested in inventory, which is not included in the analysis (according to the methodological framework proposed and previously explained in depth in paragraph 3).

(2) *Annual investment costs represent about the 85 percent of total annual storage costs*. As a direct consequence of the previous remark, total annual Investment Costs (which represent the fixed cost portion of the entire system) have the greatest impact on total holding costs, ranging between 79 and 87.5 percent of the total annual storage costs, with a mean value of 85.2 percent (in Table V). Otherwise, total annual operation costs ranges between 12.5 and 21 percent of the total annual storage costs (in Table V). The initial investment made by these five companies ranges between 303€ and 432€ per pallet position with a mean value of 369€ totally invested per pallet position.

(3) *The use of standard ranges of variation for each cost seems justified*. Since the data collected support the empirical evidence that about 85 percent of total annual storage costs are fixed and dependent on the storage capacity required, none of the considerations made for manual warehousing systems can be applied to automatic systems. In automatic environments, in fact, the specific industrial reality of operation is less important in defining the right inventory holding costs and standard cost variation ranges can be provided successfully (as reported in Table V) to help managers in the correct analysis and quantification of the annual storage cost per pallet position.

6. Relevance to industry

On the practical side, logistics and operation managers activities usually include inventory control and optimization tasks: the first deals with minimizing the total cost of inventory, while the second relates to the decision on the amount of stock to have, the quantity to be purchased and the exploration of possible alternative investments in different kind of warehousing systems. Several previous researches stress the concept that companies really interested in controlling and reducing inventory costs tend to achieve superior results when using a correct and precise holding cost rate measurement (i.e. Plossl, 1967/1985; Harris, 1990; Lee and Billington, 1992; Stock and Lambert, 1993; Richardson, 1995; Gaither, 1996, etc.). Thus, inventory carrying cost represents one of the most important factors in logistics performances; its importance is also matched by the large number of inventory models developed with unitary holding cost per item as input variable. Government and industry computerized inventory systems usually do not correctly calculate the inventory carrying cost of items stored. In the same time, a few works in literature discuss methods for calculating it (i.e. Corbacỳoglu *et al.* (2007); Berling, 2008) and example of numerical spreadsheets are missing. Despite the fact that inventory carrying cost rate had been already studied, this appears to be the first study to offer a systematic collection of real industrial data and cost component parameters. The methodological framework followed by the two study groups is based on the idea that different warehousing systems require different holding cost measurements, different cost structures and different calculation approaches to cope with different automation levels used in warehousing. The five inventory holding cost values (last row in Table II) obtained by

Table V. AS/RS warehousing systems annual storage costs in % of the total annual storage cost derived by the study group 2 results[a]

Industrial case	Case F	Case G	Case H	Case I	Case J	Variation range	
Storage capacity (pallet positions)	9,940	13,050	20,700	50,500	80,000		
Annual investment costs (% of total annual storage costs)							€/pallet position
1. AS/RS machines installed*	28.8	28.1	26.8	23.1	7.4	23.1-28.8*	10.0-20.4*
2. Racks installed	19.4	25.5	29.2	39.9	53.2	19.4-53.2	13.8-18.5
3. Control system	3.5	3.6	3.3	2.0	1.8	1.8-3.5	0.6-2.5
4. Fire protection	8.3	5.7	4.4	1.9	1.6	1.6-8.3	0.5-5.9
5. Aisle equipments	6.0	6.7	8.0	5.1	7.2	5.1-7.2	2.2-4.2
6. WHMS and HAS system (HW and SW)	2.1	1.1	1.3	0.7	0.6	0.6-2.1	0.2-1.5
7. Installation and testing	0.5	0.8	0.5	0.4	0.3	0.3-0.7	0.1-0.4
8. Training	0.9	0.7	0.6	0.2	0.2	0.2-0.9	0.1-0.6
9. Conveyor system	3.7	5.5	4.4	4.4	1.7	1.7-5.2	0.6-3.1
10. Land and building	5.8	8.8	7.9	9.7	13.5	5.8-13.5	4.0-4.9
Total annual capital costs	79.0	86.3	86.4	87.3	87.5	79.0-87.5	30.4-55.9
Annual operation costs (% of total annual storage costs)							€/pallet position
1. Indirect labor	5.8	1.4	1.9	1.7	2.5	1.3-5.8	0.7-4.1
2. Supervision	0.9	0.8	0.7	1.6	1.6	0.6-1.6	0.3-0.7
3. Heat, light, power	11.1	8.6	6.8	5.1	4.9	4.9-11.1	1.7-7.8
4. Maintenance	2.4	1.6	1.4	1.6	1.6	1.6-2.4	0.6-1.7
5. Product damage	0.9	1.4	2.8	2.7	1.9	0.9-2.7	0.6-1.4
Total annual operation costs	21.0	13.6	13.6	12.7	12.5	12.0-21.0	4.4-14.9

Note: [a]The cost for "AS/RS machines installed" does not consider the case study J since it is largely affected by the use of only four steering AS/RS machines out of 16 aisles, while the others four cases apply traditional rectilinear AS/RS machines, one per aisle.

the first study group (case studies A-B-C-D-E) completely support the state of the art and the traditional rule of thumb of the 25 percent as a mean value of the holding cost rate, supporting our computation.

The analysis conducted on the first group of industries demonstrates that in traditional manual warehousing systems, semi-evident and hidden inventory storage costs must be carefully understood and measured since they could be equal or even higher than evident costs, becoming a relevant part of the final inventory cost parameter h (the traditional annual holding cost rate): this happened in four case studies out of the five. Holding cost parameters in manual warehousing systems are close to 25 percent of the inventory on hand, and sometimes (see case E) even ten points more. Thus, our results completely support and confirm previous works on this field and suggest, one more time, that the average unitary holding cost rate of an item is equal or superior to 25 percent. In such warehousing context, a reduction in inventory quantities not only leads to a reduction of opportunity costs, operational costs (storage/retrieval) and handling costs (clearly, in a smaller warehouse, the travel times for order-handling are smaller), but, it also opens the possibility of warehouses equipments reconfiguration with a consequent reduction of floor storage, and more room available for production activities. Under these assumptions, no fixed inventory cost exist and the total inventory cost computed in this study becomes equal to the marginal inventory cost of keeping one more unit in stock, times several inventory models.

On the contrary, when an highly automated (i.e. AS/RS) warehousing system is considered (case studies F-G-H-I-L in the second working group) as in case study 2, the right holding costs computation allows to divide the marginal cost of keeping one more unit/pallet in the warehouse (the operation cost portion reported in Table IV added to the opportunity cost) from the fixed cost of a storage location (the investment portion in Table IV). In highly automated warehousing systems, due to the high capital invested, fixed costs make up the main part of the total inventory cost: in average, 85.5 percent of total annual inventory storage costs are represented by investment costs, which are directly linked to the system storage capacity rather than to the inventory value on hand or to the kinematics performances of AS/RS systems. Under this considerations, the marginal cost of keeping one more unit in stock for a certain time period (in this work we assume a time period of one year) in AS/RS warehousing systems is directly linked only to the operation costs portion, that represents about the 15 percent of the total annual storage costs (as case studies demonstrate).

Consequently, automated warehouses, if correctly managed through robust inventory cost rates, always work with really high saturation percentage (the mean number of stored unit loads out of the total warehouse capacity – still expressed in unit loads), from 90 to 99 percent, and by using the parameters computed in Table V it is possible to stress this objective and achieve high performances.

7. Conclusion

Determining the unitary holding cost of goods stored in the warehouse is an important managerial task which is becoming critical due to the increasing array of variants in many warehousing systems.

The multi-case study presented applies a methodological framework subdivided into two computational approaches directly derived by the two study group in consideration. As far as the authors know, this work seems to be the first in providing a precise cost structure subdivision for inventory cost computation.

In conclusion, the ability to measure inventory holding cost parameters in ten different case studies and finally providing a consistent set of inventory holding cost parameters is one of the most important and value-adding results of this research. Limitations still exist in term of the number of companies involved in this multi-case study: even if they are ten well-selected Italian SMEs, new researches should be addressed to explore in depth-specific industrial sectors in order to provide logisticians and managers with new empirical data and numerical examples. Moreover, a deeper analysis of automatic warehousing systems (i.e. the A-frame systems for pharmaceuticals and medical materials often applied in the healthcare sector and electronics) need to be deeply investigated by an economic point of view.

References

Alfares, H.K. (2007), "Inventory model with stock-level dependent demand rate and variable holding cost", *International Journal of Production Economics*, Vol. 108 Nos 1-2, pp. 259-265.

Azzi, A., Battini, D., Faccio, M., Persona, A. and Sgarbossa, F. (2011), "Innovative travel time model for dual-shuttle automated storage/retrieval systems", *Computers & Industrial Engineering*, Vol. 61, pp. 600-607.

Battini, D., Grassi, A., Persona, A. and Sgarbossa, F. (2009), "A new methodological framework to implement an RFID project and its application", *International Journal of RF Technologies: Research and Applications*, Vol. 1, pp. 77-94, ISSN: 1754-5730.

Battini, D., Grassi, A., Persona, A. and Sgarbossa, F. (2009), "Consignment stock inventory policy: methodological framework and model", *International Journal of RF Technologies: Research and Applications*, Vol. 48, pp. 2055-2079, ISSN: 0020-7543.

Battini, D., Gunasekaran, A., Faccio, M., Persona, A. and Sgarbossa, F. (2010), "Consignment stock inventory model in an integrated supply chain", *Int. Journal of Production Research*, Vol. 48 No. 2, pp. 477-500.

Beltran, J.L. and Krass, D. (2002), "Dynamic lot sizing with returning items and disposals", *IIE Transactions*, Vol. 34 No. 5, pp. 437-448.

Berling, P. (2008), "Holding cost determination: an activity-based cost approach", *International Journal of Production Economics*, Vol. 112 No. 2, pp. 829-840.

Berling, P. and Rosling, K. (2005), "The effects of financial risks on inventory policy", *Management Science*, Vol. 51 No. 12, pp. 1804-1815.

Bregman, R.L., Ritzman, L.P. and Krajewski, L.J. (1989), "A heuristic algorithm for managing inventory in a multi-echelon environment", *Journal of Operations Management*, Vol. 8 No. 3, pp. 186-208.

Cattani, K.D., Jacobs, F.R. and Schoenfelder, J. (2011), "Common inventory modeling assumptions that fall short: arborescent networks, Poisson demand, and single-echelon approximations", *Journal of Operations Management*, Vol. 29 No. 5, pp. 488-499.

Choi, S. and Noble, J. (2000), "Determination of economic order quantities (EOQ) in an integrated material flow system", *International Journal of Production Research*, Vol. 38 No. 14, pp. 3203-3226.

Clendenen, G.W. and Rinks, D.B. (1996), "The effect of labour costs holding costs and uncertainty in demand on pull inventory control policies", *Int. Journal of Production Research*, Vol. 34, pp. 1725-1738.

Corbacỳoglu, U., Erwin, A. and van der, Laan (2007), "Setting the holding cost rates in a two-product system with remanufacturing", *International Journal of Production Economics*, Vol. 109, pp. 185-194.

Daugherty, P.J., Chen, H. and Ferrin, B.G. (2011), "Organizational structure and logistics service innovation", *International Journal of Logistics Management*, Vol. 22 No. 1, pp. 26-51.

Defee, C.C., Williams, B., Randall, W.S. and Thomas, R. (2010), "An inventory of theory in logistics and SCM research", *International Journal of Logistics Management*, Vol. 21 No. 3, pp. 404-489.

Gaither, N. (1996), *Production and Operations Management*, Duxbury Press, Belmont, CA.

Giri, B.C., Goswami, A. and Chaudhuri, K.S. (1996), "An EOQ model for deteriorating items with time-varying demand and costs", *Journal of the Operational Research Society*, Vol. 47 No. 11, pp. 1398-1405.

Goh, M. (1992), "Some results for inventory models having inventory level dependent demand rate", *International Journal of Production Economics*, Vol. 27 No. 1, pp. 155-160.

Goyal, S.K. (2000), "On improving the single-vendor single-buyer integrated production inventory model with a generalized policy", *European Journal of Operational Research*, Vol. 125 No. 2, pp. 429-430.

Grubbstrom, R.W. (1980), "A principle for determining the correct capital costs of work in progress and inventory", *Int. Journal of Production Research*, Vol. 18, pp. 250-271.

Harris, E.W. (1990), "How many parts to make at once", *Operations Research*, Vol. 38, pp. 947-950.

Hill, R.M. (1997), "The single-vendor single-buyer integrated production-inventory model with a generalized policy", *European Journal of Operational Research*, Vol. 97, pp. 493-499.

Lee, H.L. and Billington, C. (1992), "Managing supply chain inventory: pitfalls and opportunities", *Sloan Management Review*, Spring, Vol. 33 No. 3, pp. 65-73.

Persona, A., Battini, D., Manzini, R. and Pareschi, A. (2007), "Optimal safety stock levels of subassemblies and manufacturing components", *International Journal of Production Economics*, Vol. 110, pp. 147-159.

Plossl, G.W. (1967/1985), *Production and Inventory Control*, 2nd ed., Prentice Hall, Englewood Cliffs, NJ.

Pyke, D.F. and Cohen, M.A. (1994), "Multiproduct integrated production-distribution systems", *European Journal of Operational Research*, Vol. 74, pp. 18-49.

Randall, W.S., Nowicki, D.R. and Hawkins, T.G. (2011), "Explaining the effectiveness of performance-based logistics: a quantitative examination", *International Journal of Logistics Management*, Vol. 22 No. 3, pp. 324-348.

Richardson, H. (1995), "Control your costs then cut them", *Transportation & Distribution*, Vol. 36 No. 12, pp. 94-96.

Roodbergen, K.J. and Vis, I.F.A. (2009), "A survey of literature on automated storage and retrieval systems", *European Journal of Operational Research*, Vol. 194 pp. 343-362.

Schonberger, R.L. and Knod, E.M. Jr (1997), *Operations Management Customer-Focused Principles*, Irwin/Mcgraw-Hill, Boston, MA.

Singhal, V.R. and Raturi, A.S. (1990), "The effect of inventory decisions and parameters on the opportunity cost of capital", *Journal of Operations Management*, Vol. 9 No. 3, pp. 406-420.

Stock, J.R. and Lambert, D. (1993), *Strategic Logistics Management*, Irwin/Mcgraw-Hill, Illinois, IL.

Teunter, R.H., Van der Laan, E. and Inderfurth, K. (2000), "How to set the holding cost rates in average cost inventory models with reverse logistics?", *Omega*, Vol. 28 No. 4, pp. 409-415.

Thiagarajan, S. and Rajendranz, C. (2003), "Scheduling in dynamic assembly job-shops with jobs having different holding and tardiness costs", *Int. Journal of Production Research*, Vol. 41 No. 18, pp. 4453-4486.

Van den Berg, J.P and Zijm, W.H.M. (1999), "Models for warehouse management: classification and examples", *International Journal of Production Economics*, Vol. 59, pp. 519-528.

VujoBevi, M., Petrovika, D. and Petrovikb, R. (1996), "EOQ formula when inventory cost is fuzzy", *International Journal of Production Economics*, Vol. 45, pp. 499-504.

Wilson, R.H. (1934), "A scientific routine for stock control", *Harvard Business Review*, Vol. 13, pp. 116-128.

Further reading

Stock, J.R. and Lambert, D.M. (1987), *Strategic Logistics Management*, 2nd ed., Irwin, Homewood, IL.

Wu, Y., Frizelle, G. and Efstathiou, J. (2007), "A study on the cost of operational complexity in customer-supplier systems", *International Journal of Production Economics*, Vol. 106, pp. 217-229.

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1. Pilar I. Vidal-Carreras, Jose P. Garcia-Sabater, Julio J. Garcia-Sabater. 2017. A practical model for managing inventories with unknown costs and a budget constraint. *International Journal of Production Research* **55**:1, 118-129. [CrossRef]
2. Chengfeng Wu, Qiuhong Zhao. 2016. Two retailer–supplier supply chain models with default risk under trade credit policy. *SpringerPlus* **5**:1. . [CrossRef]
3. Jörg M. Ries, Christoph H. Glock, Kurt Schwindl. 2016. The influence of financial conditions on optimal ordering and payment policies under progressive interest schemes. *Omega* . [CrossRef]
4. Yuan-Shyi Peter Chiu, Peng-Cheng Sung, Singa Wang Chiu, Chung-Li Chou. 2015. Mathematical modeling of a multi-product EMQ model with an enhanced end items issuing policy and failures in rework. *SpringerPlus* **4**:1. . [CrossRef]
5. Dilay Çelebi. 2015. Inventory control in a centralized distribution network using genetic algorithms: A case study. *Computers & Industrial Engineering* **87**, 532-539. [CrossRef]
6. Alessandro Andriolo, Daria Battini, Robert W. Grubbström, Alessandro Persona, Fabio Sgarbossa. 2014. A century of evolution from Harris#s basic lot size model: Survey and research agenda. *International Journal of Production Economics* **155**, 16-38. [CrossRef]