Proceedings of 2013 International Conference on
Technology Innovation and Industrial Management
29-31 May 2013, Phuket, Thailand

# APPLICAABILITY OF THE (Q,R)-MODEL IN MAINTENANCE METERIALS MANAGEMENT

**Antti Puurunen*, Department of Industrial Engineering and Management,
University of Oulu, P.O. Box 4610, FI-90014, Finland,
antti.puurunen@oulu.fi**

**Jukka Majava, Department of Industrial Engineering and Management,
University of Oulu, P.O. Box 4610, FI-90014, Finland,
jukka.majava@oulu.fi**

**Hanna Kropsu-Vehkapera, Department of Industrial Engineering and Management,
University of Oulu, P.O. Box 4610, FI-90014, Finland,
hanna.kropsu-vehkapera@oulu.fi**

**Pekka Kess, Department of Industrial Engineering and Management,
University of Oulu, P.O. Box 4610, FI-90014, Finland,
pekka.kess@oulu.fi**

## ABSTRACT

***Purpose:*** *The purpose of the research is to study the applicability of the (Q,R)-model in inventory management of the maintenance materials in investment intensive industry companies. The objective of the research is to answer the following research questions: 1. What is the applicability of (Q,R)-model in maintenance materials inventory management? What are the main challenges, if any, in applying the (Q,R)-model in maintenance materials inventory management?*

***Design/methodology/approach:*** *The research is a case study using data-analysis in answering the research questions. The case company is a Finnish steel manufacturer.*

***Findings:*** *The study results show that inventory levels are not controlled by the parameters of the (Q,R)-model which causes unnecessary stocking. One mechanism which causes inventory uncontrollability is also identified.*

***Research limitations/implications:*** *The research is based on a single case study. The maintenance management of the case company is similar to many other companies in the basic industries, but the applicability of the findings require wider empirical research.*

***Practical implications:*** *The paper suggests material managers to address more attention to the structure of the internal maintenance materials supply chain. Recommended actions for reducing the share of the uncontrollable material flows, include, for example, returns to the suppliers, better scheduled maintenance demand forecasting, and adding repairable transaction to the Computerized Maintenance Management System (CMMS).*

***Originality/value*** *– This paper presents novel results from maintenance management in process industries. The research indicates that widely applied (Q,R)-model is not a feasible method in all maintenance material applications.*

**Keywords** – Maintenance materials inventory, spare parts, inventory management, inventory control.

## INTRODUCTION

During the past decades the capital tied to the production equipment has increased. As a result, the importance of maintenance management, and therefore maintenance materials supply chain management, to the company's business has grown. In today's industrial companies maintenance costs can represent the largest part of operational budget (Garg and Desmukh, 2006), and the value of capital tied in maintenance materials inventories can be tens of millions euros (e.g. Porras and Dekker, 2008).

Maintenance can be determined as activities, either technical or administrative, needed to maintain and restore the desired operation condition of the production equipment or any other physical asset (Muchiri et al., 2011). Maintenance activities are typically divided into two fundamental types – reactive and proactive maintenance (Kothamasu et al., 2006). Reactive maintenance can be seen as corrective activities which are carried out only after the equipment breakdown, and proactive as activities which are carried out before the breakdown. The taxonomy of maintenance activities is more clearly shown in Figure 1. In addition, the activities aiming to reduce the future need of maintenance or to improve the operation of the equipment have been, in some cases, specified as a class of aggressive maintenance. In this study, the aggressive maintenance does not fit to our earlier stated maintenance determination (Swanson, 2001).

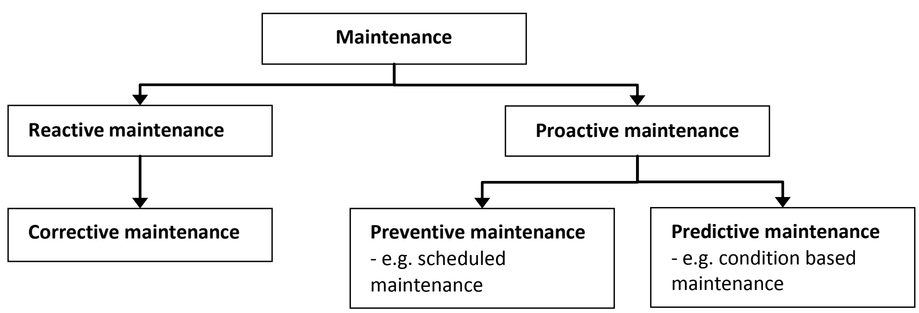


**Figure 1.** Taxonomy of maintenance activities (modified from Kothamasu et al., 2006).

Supply chain management of maintenance materials, i.e. spare parts and consumables needed for the maintenance, is essential for ensuring the operational reliability. Unavailability of maintenance material can cause extended downtime, which in critical process phase leads to high costs. In addition to the high availability requirements, other characteristics of maintenance materials are sporadic demand and relatively high price of individual item (Huiskonen, 2001).

Management of the supply chain, and especially inventory management, is challenging because of the nature of maintenance. For proactive maintenance, it may be possible to procure materials to arrive just when needed to avoid unnecessary warehousing. For corrective maintenance, stock outs can cause significant production loss and a safety stock is typically needed (Kennedy et al., 2002). The function of the inventory therefore derives from the needs of the maintenance and the size of the inventory depends on the production equipment's maintenance policy. These aspects differentiate the management of maintenance materials inventory from other manufacturing-related inventories.

Despite special characteristics, the maintenance materials inventory management typically relies on traditional inventory management theories and practices, e.g. Economic Order Quantity (EOQ), developed by Harris (1913), and reorder point method with fixed or non-fixed order quantity. In industrial maintenance context, the inventories, or at least part of the inventory items, are often controlled by continuously reviewed fixed order quantity (Q) and reorder point (R) inventory model, i.e. (Q,R)-model (Figure 2).

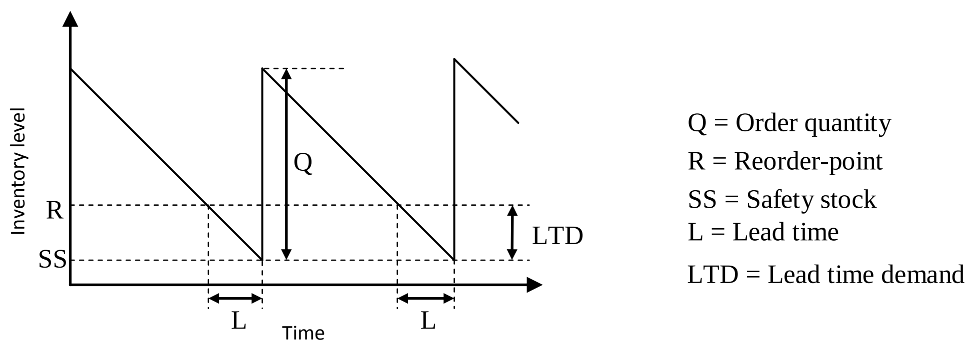


**Figure 2.** Logic of continuously reviewed fixed order quantity inventory model (Tersine, 1984).

In the (Q,R)-model, the replenishment orders are fully controlled by the parameters Q and R. The R expresses when to order and the Q expresses how much to order. Buyer needs to decide only the supplier. Because the model controls the amount and frequency of inbound material flow to the inventory, the inventory optimization is typically seen as optimization of the parameters (e.g. Chang et al., 2005). However, not enough attention has been addressed to the (Q,R)-model's applicability to the maintenance context, where other inbound sources besides replenishment orders may exist. These include, for instance returns.

In this research the applicability of the (Q,R)-model, utilized in the case company's inventory management, is analyzed. The main aim of the study is to research whether the applied model can manage the inventory level in a sound way and what is needed for better control of the inventory. The applicability is analyzed by answering following research questions:

1. What is the applicability of (Q,R)-model in maintenance materials inventory management?
2. What are the main challenges, if any, in applying the (Q,R)-model in maintenance materials inventory management?

## LITERATURE REVIEW

In the early 2000s, the research of maintenance materials supply chain management focused on its differences to the conventional logistics. At that time, the maintenance materials were identified to have characteristics, e.g. sporadic demand, high service-level requirements and high price, which affect the inventory management (Huiskonen, 2001). More recently, the demand of the maintenance materials has been linked to the maintenance policy of the production equipment (Wang and Syntetos, 2011) and several studies about joint optimization of maintenance and inventory emerged (Van Horenbeek et al., 2012).

In the inventory management research generally, the (Q,R)-model is widely applied in the last decades and lot of extensions have been made to adapt the model better to its context, e.g. demand uncertainties and backordered/lost-sale stock-out policy (Williams and Tokar, 2008). The models have evolved to be context-specific due to the different requirements in operating environments, e.g. deteriorating items, supply chain structures, etc.

In industrial maintenance, the structure of the supply chain differs from the assumptions of the (Q,R)-model. In addition to the obvious supplier-inventory-customer material flow, also other flows exist. For example, some spare parts may be in the internal repair cycle, where used parts are recovered for future use by the plant’s repair shop. Also unused spares can be returned to the inventory. Driessen et al. (2010) refer to these other flows as part return streams. Driessen et al. (2010) propose a delay time between the material request and demand registration; if the request is not justified, it can be returned to the inventory within the delay and no new purchase order is triggered. In the model, only external suppliers replenish the inventories.

Wang and Syntetos (2011) continued contributing to this phenomenon by making a distinction between material requests arisen from the proactive or reactive maintenance. For reactive maintenance, the requested amount is typically deterministic but the moment when the need arises is stochastic, while, for proactive maintenance, requested amount is stochastic but the moment when the need arises is deterministic. Practically, this means, that from proactive maintenance activities, returns of excess materials to the inventory may cause a significant source.

Product returns and their impact on the inventory management have been studied widely from reverse logistics point of view. Fleischmann et al. (1997) discuss a system, where a certain share of demand returns to the inventory as recovered products. A clear distinction can be made between the recovered returns and the unused returns, and for repairable maintenance materials management, e.g. the METRIC-model (Sherbrooke, 2004) can be applied.

Unused material returns are a common challenge especially in catalogue/internet mail order retail business, due to the customers’ legal right to return the product without expenses. In that context generally, Mostard and Teunter (2006) observed the return rate to be approximately 35-40 % of deliveries, and applied the newsboy problem to it with promising results.

## RESEARCH PROCESS

The research process of the study is shown in Figure 3.


**Figure 3.** Research process.

The study started with reviewing the relevant literature. The recent research of maintenance materials supply chain management, (Q,R)-inventory model and product returns were reviewed. The second phase is the planning of the case study.

The research aims to answer whether the assumptions of the (Q,R)-model are realistic in the maintenance context. For this purpose, a case study was seen an appropriate research strategy. The research strategy was preferred because of the research environment. The focus of the study is on a contemporary phenomenon, i.e. maintenance materials supply chain, within the real-life context. The design of the study is an embedded single case design. Not much can be said about the functionalities of the inventory at inventory level, so we pay attention to the subunits, e.g. inventory items and transactions. A major risk of this kind of study is that the original target of the study becomes the context. To avoid the research becoming an inventory item and transaction study, the results of subunit analysis are presented in relation to the whole inventory. (Yin, 2003.)

The rationale for the selection of the case company is a mix of critical and typical case. From the maintenance point of view, the maintenance-intensive company represents the critical case. Maintenance has particularly significant impact on the case company's business and therefore it can be assumed to be well managed. From heavy process industry, or computerized maintenance management system (CMMS) point of view, the company is assumed representing a typical case. (Yin, 2003.)

The data collection from the CMMS includes all inventory transactions recorded in 2011 for all inventory items determined as maintenance materials. Practically, two databases, inventory item database limited to maintenance materials and inventory transaction database were combined by using the item identification code as a join. The current inventory level and current control parameters were available from the inventory item database. In the analysis phase, the MS Excel and MS Access were used. The item selection is more detailed presented in the case company section.

The current state of the inventory controllability is analyzed by comparing the contemporary inventory level to the situation where the inventory level is controlled by the control parameters. After analyzing the inventory levels, the transaction types are investigated to identify different material channels and their impact and significance to the inventory value.

**Case company**

The company under research was a Finnish steel manufacturer listed on the Helsinki Stock Exchange. The company currently has operation units globally, but its largest steel mill, where the study was conducted, is located in Finland.

At the time of the study (2012), for maintenance materials, there was one main storage facility and there were nine smaller production-unit-specific storage facilities at the site. There were almost 40,000 items kept in stock, and the value of the capital tied in these inventories was tens of millions euros. In addition, there were the vendor managed main inventory and the smaller satellite inventories, also managed by the vendor, around the site. However, the value of material replenishments and consumption was highly concentrated in the mill's main storage facility.

The actual stock control is based on a fixed order quantity and reorder-point method, where a new purchase request with the stated quantity takes place every time the storage level reaches the reorder point. Responsibility for these item-specific control parameters was designated to a relevant department. Usually this department was the one using the item, or the material management department, which was also responsible for the management of all storage facilities at the site. No systematic or instructed procedure existed for the determination or the optimization of the parameters.

The order-quantity and reorder-point optimization was thought in the company to be a primary development effort in inventory management because of the previous attempts to reduce the tied capital had been unsatisfactory. However, before the optimization project the company wanted to have a comprehensive picture about the factors affecting to the inventory levels currently.

In the CMMS, the inventory items are classified according to Table 1. In the company, maintenance materials were seen including the physical items in the classes 2-7. 38 774 inventory items existed after service items were excluded. Obviously, maintenance materials are not a homogenous group of items and demand patterns and supply characteristics vary between items.

**Table 1**. Material classes in the CMMS.

| Class | Name |
|---|---|
| 0 | Basic materials |
| 1 | Refractories |
| 2 | Consumable machine parts |
| 3 | Piping and HVAC consumables, hydraulics and pneumatics |
| 4 | Electrical devices, instruments and spare parts |
| 5 | Electrical installation consumables and electronic components |
| 6 | Power transmission, lifting and moving devices |
| 7 | Machine and construction elements |
| *8* | Typed structures |
| 9 | Tools, safety and security equipment |

## RESULTS

### 1. Inventory level controllability

In (Q,R)-model, the inventory level is controlled by the parameters. In table 2, the control parameters (Q) and (R) with item's price and current inventory levels (CL), are shown for four items. The stock expresses how many years the current inventory level would meet the demand if the future demand is projected from the past five and half year consumption. For all of these items, the inventory level is relatively high in the light of the past consumption and current control parameters.

**Table 2**. Example maintenance inventory items.

| Item ID | Q | R | Price | CL | Stock |
|---|---|---|---|---|---|
| *666388* | *11.67* | *10.00* | *327 €* | *476* | *12.5* |
| *173427* | *3.50* | *4.00* | *20 660 €* | *9* | *2.60* |
| *364265* | *0.08* | *1.00* | *5300 €* | *6* | *4.71* |
| *302901* | *0.08* | *1.00* | *3590 €* | *7* | *19.3* |

Current inventory levels (Table 2) shows, that the inventory levels do not follow the parameters. Consequences of the inventory uncontrollability are evaluated by estimating the inventory level in the situation where the inventory level is fully obeying the control parameters. In the (Q,R) context, the average inventory level can be approximated by using e.g. Hadley-Whitin's (1963) method. However, it is unknown, how well the instantaneous view describes the average inventory at item level. Another restriction of the use of the Hadley-Whitin's expression is that the value of safety-stock remains unknown. Therefore the portion of overstock has been estimated in two ways:

**Method 1**. *Overstock = CL - (Q + R), and*
**Method 2**. *Overstock = CL - (½Q + R).*

For example, item's 666388 (Table 2) overstock by using method 1 can be calculated as 454.33 units which equals 148 566 € or 95.4% (Overstock/CL). By using method 2 the overstock equals 460.17 units which is 150 474€ or 96.7% of total inventory value of the item.

In Table 3, the overstock of all inventory items has been added together and shown as a share of the total inventory value. Totally, the inventory level exceeds the maximum level (Method 1) for every fourth item and the value tied to the exceeding share is 19.1% of the total inventory. The average level (Method 2) exceeds for 42% of items and the exceeding value is 36.2% of total inventory.

**Table 3**. Shares of overstock.

| Estimation method | Method 1 | | Method 2 | |
|---|---|---|---|---|
| | **Items** | **Overstock** | **Items** | **Overstock** |
| **Results** | 9312 | 19.1 % | 16295 | 36.2 % |

**2. Causes of overstocking**

The study of the mechanism, which is causing the excess in inventory levels, started with the identification of the transaction types. In the CMMS, there were 17 different types of transaction to get the materials into or out of the inventory. Those transactions are shown in the Table 4.

**Table 4**. Inventory transaction types in CMMS.

| | Description | Out transactions | Description |
|---|---|---|---|
| *Material transactions:* | | | |
| **Receipt of purchase order** | *Arrival of purchase order triggered from R* | **Returns to supplier** | *Return of non-conformance goods* |
| **Return of pick-up** | *Return of material due to the oversized pick-up* | **Pick-ups for consumption** | *Material pick-up for maintenance activity* |
| **Transfer in** | *Material transfer from other storage facility* | **Transfer out** | *Material transfer to other storage facility* |
| **Return without order** | *Material return which are not related any pick-up* | **Cancellation of return without order** | *Cancellation of return without order* |
| **Stock-taking, gain** | *Stock-taking correction > 0 €* | **Stock-taking , loss** | *Stock-taking correction < 0 €* |
| | | **Scrap** | *Material pick-up for to be scrapped* |
| **Return from sale** | *Return of material on sale* | **Pick-up for sale** | *Material pick-up for to be sold* |
| *Corrections:* | | | |
| **Manual price change** | | **Manual price change** | |
| **Transfer correction** | | **Transfer correction** | |

Material can be brought to the inventory with receipt of purchase order; returns to inventory; transfers in; returns without order; stock-taking or returns from sale transaction. Receipts of purchase orders (RPO) were caused by conventional purchases triggered from the re-order point. Returns without order (RwO) resulted from the returns of the direct purchases which can be caused by scheduled maintenance or investments, but also in-house reparable spare parts were brought to the inventory with this transaction. Return of pick-up was the way to return the excess material caused by oversized amount of pick-up. Transfer transactions are for the material transfers between different storage facilities.

Materials can be moved out of the inventory for returns to supplier; pick-up for consumption (PU); transfer out; cancellation of return without order; stock-taking; scrap and pick-up for sale transaction. The main channels out of the inventory were pick-ups for consumption, returns to suppliers and transfers out. Main channels to the inventory were replenishment orders, returns without order and returns from pick-ups. In addition to the physical material transactions, records can be corrected by manual price changes or transfer corrections.

The cumulative value of transaction types in 2011 are presented in the table 5. The main transactions to the inventory included the receipt of purchase order, return without order and return of pick-up. Main out transaction types included pick-ups for consumption, transfer out and returns to supplier.

**Table 5**. Values of transaction types in 2011
.

| In transactions | Value | Out transactions | Value |
|---|---|---|---|
| Receipt of purchase order | *14.28 M€* | Returns to supplier | *0.89 M€* |
| Return of pick-up | *1.43 M€* | Pick-ups for consumption | *18.2 M€* |
| Transfer in | *0.90 M€* | Transfer out | *0.90 M€* |
| Return without order | *6.59 M€* | Cancellation of return without order | *0.09 M€* |
| Stock-taking, gain | *0.73 M€* | Stock-taking , loss | *0.34 M€* |
| | | Scrap | *0.06 M€* |
| Return from sale | *0* | Pick-up for sale | *0* |
| Total | *23.93 M€* | Total | *20.48 M€* |

Values of the major transaction types, including RPO, RwO and PU, are presented monthly in Figure 4. The sum value of transactions (SVT) presents the amount of increase or decrease in inventory value when month’s in and out transactions are summed.

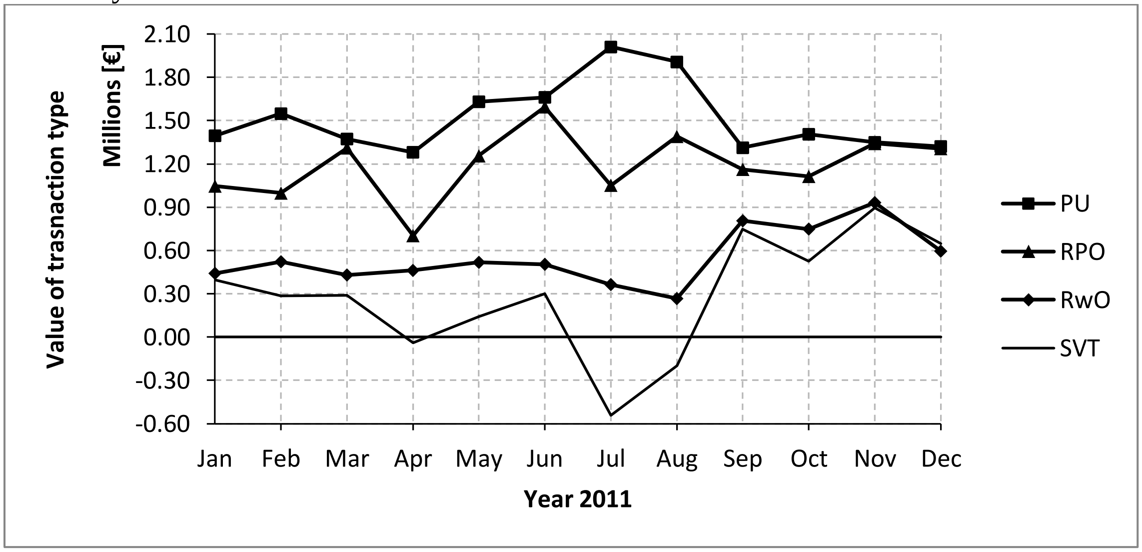


**Figure 4**. Monthly values of transaction types in 2011.

The SVT has risen to higher level starting from September, which means increasing inventory value. Actually, the SVT remained below zero only for a short period of time. The trend was confirmed directly from the inventory value by analyzing the monthly value during the year 2011. The change to higher level in SVT is caused mainly by increase in returns without order and decrease in pick-ups for consumption, while receipts of purchase orders stay quite flat.

The summer season is typically intensive maintenance period, which obviously affects to the patterns. The unique aspect of the year was the completion of the major investment project in August, which may appears in the results. A systematic event or error, which causes the raised returns without order since August, was not found.

### 3. Major material flows in and out of the inventory

The most significant transactions or materials flows to the inventory were replenishment orders, returns without order and returns to inventory. Pick-ups for consumption were the main outbound flow. The major material flows are shown cumulated in the figure 5 where inventory is set in between of the suppliers and maintenance, i.e. customers.

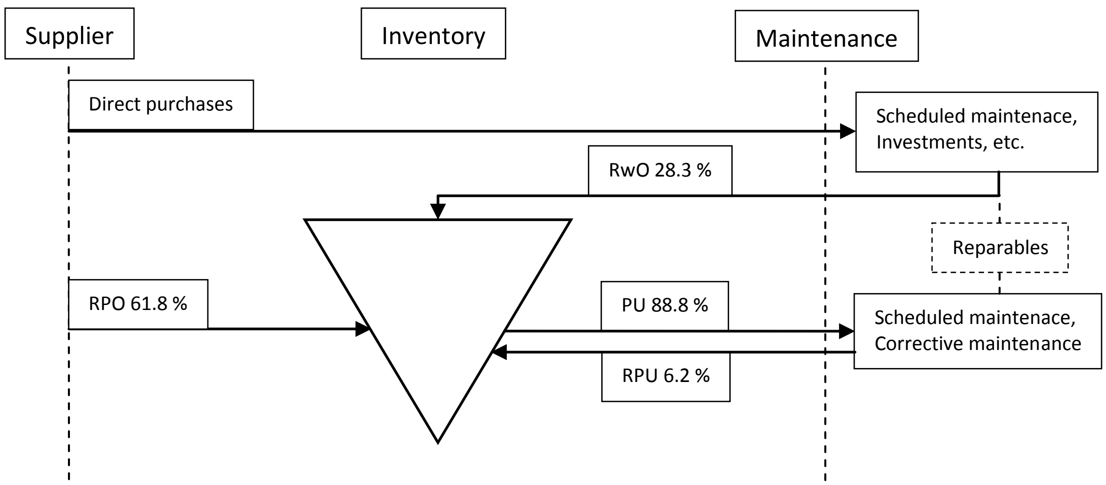


**Figure 5.** Cumulated material flows into and out of the inventory in 2011.

The conventional replenishment orders (RPO) is not the only significant intake of the inventory. RwO describes the returns without order and RPU describes returns of pick-ups to the inventory. RPO is controlled at item level by control parameters, i.e. order quantity (Q) and reorder point (R), but RwO and RPU cannot be controlled directly by control parameters, because they are caused by incorrectly estimated consumption.

## DISCUSSION

In general, the maintenance inventory level in the case company is not fully controlled by the control parameters of the (Q,R)-model, resulting in the unnecessary inventory. The share of overstock depends on reference value used in the estimate. If the reference inventory level is the absolute maximum level enabled by the parameters, the current overstock represents 19.1% of total inventory value. More realistic view of consequences of uncontrollability can be obtained if the current inventory level is compared to the approximated average level, resulting in 36.2% overstock estimate.

The study reveals that there are multiple ways to procure materials using the CMMS, enabling the uncontrolled material flows to the inventory. Thus, the phenomenon of overstocking is permitted. Over a third of the total material flow to the inventory consisted of uncontrolled returns. Increased level of returns and decreased consumption also explain the faster accumulating inventory value starting from September 2011.

In such an environment, the (Q,R)-model is incapable to ensure the material availability in economically sound manner. Especially returns without order (RwO) needs a special attention because it adversely affects to the function of the (Q,R)-model. Because of the RwO, only the lower boundary of the inventory level can be ensured. This means that the service-level can be ensured by the control parameters but, practically, no upper limit to the item's inventory value exists. This also reduces the potential benefits of parameter optimization. Returns of pick-up to the inventory (RPU) can cause a similar effect but with a distinctly smaller magnitude.

### 1. Theoretical implications

Driessen et al. (2010) describe the structure of the maintenance materials supply chain in the industrial context, but they assume the replenishment orders to be the only way to purchase, which limits at least partially the upper boundary of item's inventory level. For, example, if the material return leads to an unnecessary replenishment, the second replenishment is prevented until the inventory level reaches the reorder-point again. In the case studied in this paper, the materials for some proactive maintenance activities and investments were purchased directly without any link to the inventory control parameters.

This research focuses on the differences between the basic assumptions of the (Q,R)-model and the real context. These basic assumptions are widely hypothesized to take place in the maintenance related literature (e.g. Kennedy et al., 2002). The results of this study show that reality in maintenance material context makes it very challenging to manage the inventory with only two parameters: reorder point and order quantity. It can also be difficult to modify the context to fit to the assumptions of the (Q,R)-model, due to the tendency to maintain the production equipment proactively.

## 2. Managerial implications

Material managers ought to reduce the share of uncontrolled material flows to the maintenance inventory. One way is to remove the causes of these flows, and another way is to try to predetermine the amount of returns in order to take it into the account in the parameter optimization. The first way includes actions to prevent the materials to flow to the inventory, and the second different kind of forecasting techniques.

An option to remove a cause of the uncontrolled material flow is to develop the procurement policy. If unnecessary materials from scheduled maintenance can be returned to the supplier without expenses, the issue is moved to the upstream in the supply chain. A second option can be the delay time between the request and demand registration as Driessen et al. (2010) proposed.

It may be reasonable to accept a certain amount of returns and instead of total prevent, to try to forecast them as accurately as possible. An obvious action to enable the better forecasting is improving data quality. Currently, the unused product returns and reparables are mixed in the CMMS, and clarification of the data is an overwhelming task. Clearly separating the reparables from other material flows by, for example, creating a new transaction type would enable using the data more precisely. Widely studied newsboy problem (e.g. Mostard and Teunter, 2006), i.e. inventory level determination problem with uncertain demand and perishable products, may also give applicable models for material returns from proactive maintenance activities.

## CONCLUSIONS

In this paper, the basic assumptions of the (Q,R)-model turned out to be challenging to fulfill in the maintenance context. As a result, the upper boundary of the items' inventory level, set by the model, does not limit the actual inventory level. On the other hand, nothing indicates that the lower boundary would not be functioning properly. The instant view to the inventory revealed the 25% of the items having higher level than the theoretical maximum enabled by the control parameters. The share of the overstock was 19.1% of the total inventory compared to the theoretical maximum and 36.2 % compared to the theoretical average (Table 3). This means that the model is applicable from service level point of view, but not from the economic one.

The main challenges in the case company in applying the (Q,R)-model in maintenance inventory management, were the uncontrollable returns to the inventory. These returns may contain excess materials from the planned maintenance operations, reparables, and spare parts procured with some investments to the production equipment (Figure 5). The share of these returns was 28.3% of all material flows to the inventory.

In this study, the maintenance materials internal supply chain was analyzed in the case company, which limits the generalization of the results even though the case was selected from capital intensive industry. Also the data and analysis include uncertainties. For example, different kind of errors and mistakes may relate to the individual transactions. In addition to the one identified mechanism, others may exist too, so to be able to confirm the unambiguous causality between the overstocking and uncontrollable material flows, deeper research is required. Another potential direction for the future research is to identify and analyze the other inventory models than the (Q,R)-model developed to maintenance materials inventory management.

## REFERENCES


1. Driessen, M.A., Arts, J.J., van Houtum, G.J., Rustenburg, W.D., and Huisman, B. (2010), "Maintenance spare parts planning and control: A framework for control and agenda for future research", working paper, BETA Research School for Operations Management and Logistics, University of Eindhoven, September.
2. Fleischmann, M., Bloemhof-Ruwaard, J.M., Dekker, R., van der Laan, E., van Nunen, J.A.E.E., and van Wassenhove, L.N. (1997), "Quantitative models for reverse logistics: A review", *European Journal of Operational Research*, Vol. 103, No. 1, pp. 1-17.
3. Garg, A., and Deshmukh, S.,G. (2006), "Maintenance Management: literature review and directions", *Journal of Quality in Maintenance Engineering*, Vol. 12, No. 3, pp. 205-238.
4. Hadley, G., and Whitin, T. (1963), "*Analysis of Inventory Systems*, Prentice-Hall, Eaglewood Cliffs, NJ.
5. Harris, F.W. (1913), "How many parts to make at once", *Factory: The Magazine of Management*, Vol. 10, No. 2, pp. 135–136.
6. Huiskonen, J. (2001), "Maintenance spare parts logistics: special characteristics and strategic choices", *International Journal of Production Economics*, Vol. 71, No. 1–3, pp. 125–133.
7. Kennedy, W.J., Patterson, W., and Fredendall, L.D. (2002), "An overview of recent literature on spare parts inventories", *International Journal of Production Economics*, Vol. 76, No. 2, pp. 201–215.
8. Kothamasu, R., Huang S.H., and VerDuin W.H. (2006), "System health monitoring and prognostics – a review of current paradigms and practices", *International Journal of Advanced Manufacturing Technology*, Vol. 28, No. 9-10, pp. 1012-1024.
9. Mostard, J., and Teunter, R. (2006), "The newsboy problem with resalable returns: A single period model and case study", *European Journal of Operational Research*, Vol. 169, No. 1, pp. 81-96.
10. Muchiri, P., Pintelon, L., Gelders, L., and Martin, H. (2011), "Development of maintenance function performance measurement framework and indicators", *International Journal of Production Economics*, Vol. 131, No. 1, pp. 295-302.
11. Porras, E., and Dekker R. (2007), "An inventory control system for spare parts at a refinery: An empirical comparison of different re-order point methods", *European Journal of Operational Research*, Vol. 184, No. 1, pp. 101–132.
12. Sherbrooke, C.C. (2004), *Optimal Inventory Modeling of Systems: Multi-Echelon Techniques*, Kluwer Academic Publishers, Hingham, USA.
13. Tersine, R.J. (1984), *Principles of Inventory and Materials Management*, 2nd ed., North Holland, NY.
14. Van Horenbeek, A., Buré, J., Cattrysse, D., and Pintelon, L. (2012), "Joint maintenance and inventory optimization systems: A review", *International Journal of Production Economics*, Forthcoming.

15. Wang, W., and Syntetos, A.A. (2011), "Spare parts demand: Linking forecasting to equipment maintenance", *Transportation Research Part E: Logistics and Transportation Review,* Vol. 47, No. 6, pp. 1194–1209.
16. Williams B.D., and Tokar, T. (2008), "A review of inventory management research in major logistics journals: Themens and future directions", *The International Journal of Logistics Management*, Vol. 19, No. 2, pp. 212-232.
17. Yin R.K. (2003), *Case study research: design and methods*, 3rd ed., Sage Publications, Thousand Oaks, CA.

## BIOGRAPHICAL

**Antti Puurunen** is a Doctoral Student at the University of Oulu, Finland. He received his M.Sc. in Engineering from the University of Oulu, in 2012. His research interests cover maintenance materials supply chain management.

**Jukka Majava** received his M.Sc. in Engineering from the University of Oulu, Finland, in 1999. His industrial experience includes technology marketing, customer care, partner management, project management, and supply chain development at Nokia Corporation. Currently he works as a Doctoral Student in the Department of Industrial Engineering and Management at the University of Oulu.

**Hanna Kropsu-Vehkapera** (Dr.Sc.) received her MSc in Engineering, majoring in Industrial Engineering and Management, in 2005 and her Dr (Tech) in 2012, both from the University of Oulu, Finland. She currently works as a Post doctoral research fellow at the Department of Industrial Engineering and Management, the University of Oulu, Finland. Her research interests cover information management and product lifecycle management. She has some years of experience from the IT industry.

**Pekka Kess** (Dr. Sc., Dr. Eng.) is professor of Industrial Engineering and Management at the University of Oulu, Finland. He has extensive managerial experience from both universities and industrial enterprises. He has worked in managerial positions in chemical, steel and electronics industries as well as in software business. He is an active project evaluator and manager in international research and development projects. His research areas are strategic management, production organizations, knowledge management, quality management and e-Learning. He has an extensive network of partners in Europe, Asia and Americas.