Using System Dynamics in warehouse management: a fast fashion case-study

Using System Dynamics in warehouse management: a fast-fashion case study

Anna Corinna Cagliano (corresponding author) [a]
Alberto De Marco [a]
Carlo Rafele [a]
Sergio Volpe [b]

[a] Politecnico di Torino
School of Industrial Engineering and Management
Dept. of Production Systems and Business Economics
corso Duca degli Abruzzi 24, Torino 10129, Italy

[b] Miroglio Fashion S.r.l.
Logistics Direction
viale G. Nogaris 20, Bra (CN) 12060, Italy

Abstract

Purpose – To present an analysis of how different sourcing policies and resource usage affect the operational performance dynamics of warehouse processes.

Design/methodology/approach – The System Dynamics methodology is used to model warehouse operations at the distribution centre of a leading fast-fashion vertical retailer. This case study includes a detailed analysis of the relationships between the flow of items through the warehouse, the assignment of staff, the inventory management policy, and the order processing tasks.

Findings – Case scenario simulations are provided to define warehouse policies enabling increased efficiency, cost savings, reduced inventory, and shorter lead-times.

Practical implications – The case study reaffirms that a flexible usage of human resources, outsourcing of selected warehouse operations, and sourcing from reliable manufacturers may result in important performance improvements for centralised warehousing.

Originality/value – It is proved that System Dynamics is a valuable tool in the field of operations management not only to support strategic evaluations but also to execute a detailed analysis of logistical processes and make scenario-based dynamic decisions at the operational level.

Keywords Distribution, Warehouse, Operations management, Simulation, Apparel, Italy

Paper type Case Study

Word count 6,178

1. Introduction

The increasing need to improve supply chain (SC) performance has been forcing warehouses to focus on integrating the production effort with the market (Frazelle, 2002; Baker, 2007). Receiving, transferring, handling, storage, packing, and expediting operations at the warehouse directly affect the effectiveness of a company as a whole as well as its quality and logistic service level (Rafele, 2004). In this sense, a proper warehouse management process has become critical to gain competitive advantage through better customer service and shorter lead times (De Koster, 1998).

However, warehouse operations are confronted with a rising complexity tied to nonlinear relationships between performance factors (Faber *et al.*, 2002) and face increasing costs associated with the need for reducing the time-to-market. This has led SC managers to undertake cost-saving sourcing strategies (De Koster and Warffemius, 2005) integrated with efficiency-oriented management policies (Maltz and DeHoratius, 2004).

Increasing complexity and cost are particularly important to the mass apparel retail industry, where extremely short product life-cycles, seasonality, and unpredictable demand require effectual warehouse operations (Bruce and Daly, 2006). In fact, most of leading mass fast apparel retailers are fashion-followers that exploit the market by bringing new products to their stores as frequently as possible; therefore, a large variety of clothes of diverse sizes, shapes, colours, etc., are designed as late as possible to include the ultimate fashion trends and are produced and centrally distributed as quickly as possible to make them readily available to serve on store shelves in sufficient quantities to assure sales and replenishment (Christopher *et al.*, 2004). This is the industry that has spawned the agile SC and the philosophy of the quick response as a set of production, centralised inventory, and distribution management policies to increase speed and flexibility (Lowson *et al.*, 1999; Chandra and Kumar, 2000).

As far as centralised distribution is concerned, appropriate sourcing strategies from a variety of suppliers located in low-cost countries and the procurement of a temporary workforce are crucial elements that increase the system complexity but are important drivers to reach SC competitive advantage (Rollins *et al.*, 2003; Kumar and Samad Arbi, 2008).

Building on previous research, this work is aimed at understanding how different sourcing policies may affect the operational performance of a distribution centre (DC) by using a case study of an Italian apparel retailer.

The operation of the DC is illustrated by using the System Dynamics (SD) methodology. SD is considered to be a useful structural theory for operations management, which provides models as content theories of the real world systems that they represent and is known to be an effective approach for problem solving and evaluating the strategic implications of business decisions (Größler *et al.*, 2008). In addition, this case study reports a novel deployment of the SD methodology to the discipline of operations and production management with regard to some singular issues. The SD methodology in this study is used for a detailed operational analysis of a business system rather than just focusing on the overall understanding of the systems performance behaviour. Second, the methodology is specifically applied to inventory and warehouse management and proves to be a valuable technique for case-based performance improvements of industrial operations.

The paper is organised as follows. Section 2 analyses previous research on warehouse and inventory management issues. The basics of the SD modelling and simulation approach, together with its relevant applications, are presented in Section 3, whereas the main characteristics of the fast-fashion industry as well as an introduction to the case study are detailed in Section 4. The case-study model and simulation are illustrated and the results are discussed in Section 5. Finally, we draw conclusions and give future research directions.

2. Relevant research

The experience reported in this case study builds upon previous research in the fields of inventory management and warehouse operations management. Inventory management is a well-covered stream of operations management explorations providing many models and approaches for different situations (Williams and Tokar, 2008).

Warehouse operations management is also a well-covered topic of research. Some authors discuss the requirements and the benefits of effective warehouse processes (Gunasekaran *et al.*, 1999; Petersen II, 1999). Other works give suggestions on how to organise stockrooms and replenishment systems (Landers *et al.*, 2000; Huq *et al.*, 2006), about the integration of warehouse complexity with tailor-made control structures (Faber *et al.*, 2002), and regarding the links between resource allocation and warehouse decision making processes (Zomerdijk and De Vries, 2003).

However, little work is available to show the benefits of integrating inventory control with warehouse management and to propose effective approaches for integrated decision making at both strategic and day-by-day levels. To answer this deficiency and contribute to the state-of-the-art, we propose the use of SD as a structural methodology for operations management and, in particular, to support warehouse decision making based on detailed modelling of the interrelated factors affecting the warehouse operations performance and inventory management of a DC.

3. System Dynamics approach

Founded on system thinking (Forrester, 1961), SD is a computer-based modelling and simulation approach that assists in solving complex problems.

SD allows one to diagram a system of causally looped variables, define the mathematical relations between them, and instruct a computer do the discrete-step computational effort of solving the differential set of equations (Sterman, 2000).

The trends of all variables out of computer simulations are plotted over a specified period of time into the future. The validation of the model is based on historical data and sensitivity analyses.

SD provides an understanding of the overall performance behaviour of the system and of the influence of the various factors to the problem to support policy design by making simulations of different scenarios (Greasley, 2005). As a quantitative modelling methodology, SD allows the explanation of performance factors of real-life processes and capturing decision-making problems faced by managers.

In the field of SC management, SD contributes to the task by adding human-bounded rationality, information delays, managerial perceptions, and goal-setting approaches to inventory management traditional rules and control theoretic models (Akkermans and Dellaert, 2005). Yet, the number of practical applications of SD to SC that have appeared in academic literature is still limited.

Some works are concerned with the dynamic behaviour of SCs, both in the manufacturing and service sectors (Anderson and Morrice, 1999, 2000; Sterman, 2000; Panov and Shiryaev, 2003; Schieritz and Gröβler, 2003; Anderson *et al.*, 2005; Rafele and Cagliano, 2006); others involve demand planning (Ashayeri and Lemmes, 2006), capacity control, and inventory instability (White, 1999; Croson and Donohue, 2005), just-in-time production, data-driven and process-driven performance improvement and control (Gupta and Gupta, 1989).

Our model was developed to provide the case company with a valuable decision support system to implement dynamic management policies enabling performance improvement of inventory and warehouse integrated operations. Through an iterative process of scenario planning and the evaluation of outcomes and the changing of policies, insights into the dynamic nature of the organisation have been acquired (Größler, 2007). In particular, the simulation was mainly directed to ascertain the impacts of different sourcing policies for the tasks of counting incoming items and allocating warehouse personnel.

The model shows that the application of SD to business process improvement is of great practical value. This in turn demonstrates that SD can be used not only for strategic thinking but also for detailed case-based modelling and for supporting performance improvement actions in SC management.

4. The case study

This work analyses warehousing operations at the DC of a mass-fashion vertical player: Miroglio Fast Fashion Division (Miroglio), part of the Miroglio group of companies (Cagliano, 2010).

Typically, mass fast-apparel industries are global buyer-driven value chains with very short time-to-market requirements that design, procure from low-cost manufacturing sources, distribute and sell, in company-owned stores, short life-cycle clothes intended to capture the consumers' mood and edging fashion of the moment (Ghemawat and Nueno, 2006).

Market volatility, unpredictable demand, and impulse purchasing approaches make the business turbulent and dynamic. These qualities demand short manufacturing and distribution lead times, which can be achieved through a variety of means, such as automated warehousing, fast transportation, and improved manufacturing methods (Fisher and Raman, 1996). This type of business also requires prompt management reactions, timely decision making, and flexible sourcing strategies.

This kind of quick response management approach is currently applied by the most successful international companies, such as Inditex-Zara, Hennes&Mauritz, The Gap, Benetton, Miroglio, and Mango.

Miroglio, headquartered in Alba, Italy, sells women's garments and accessories at accessible prices through the Motivi, Oltre, and Fiorella Rubino brand chains. By the end of 2008, with a total annual turnover of more than one billion Euros, the company had produced approximately 20 million clothing items while operating more than 1,550 mall and town centre brand stores as well as 130 outlets around the world.

Product design is performed centrally. Production takes place partly in company-owned factories located in North Africa and partly through offshore low-wage fashionists. Worldwide distribution is managed centrally through the DC, which has 6,000 square meters of usable floor area, is located close to the headquarters, and is equipped with a huge automated sorting conveyor system. A partnering global freight forwarder executes shipments via air and truck transport.

To ensure it achieves its time-to-market goal of six to eight weeks, Miroglio is committed to perform all of these functions as quickly as possible and, in particular, to make centralised distribution operations more efficient.

4.1. Warehouse operations at Miroglio

At a glance, Miroglio's warehouse operations are structured as follows. Supplies from owned factories and fashionists are shipped to the DC, either directly or through an intermediate platform located in central Italy. The supplies are then counted, stored, picked, sorted, packed, and shipped to retail stores (Figure 1).

In more detail, boxes arrive on a truck at the DC, are unloaded by assigned teams of workers and placed in the incoming product floor area. Urgent items are picked from incoming boxes and sent directly to the sorting system, to make them available for quick loading and shipment. The remaining items are received, counted either manually or via the automated sorting system to match the receiving list with the order placed, and stored in barcode-labelled boxes, to allow for periodical inventory update. Each box contains items with uniform combination of item, size, and colour. Then the variety of items ordered by store managers is ordinarily picked and, together with urgent items, automatically sorted into boxes. Finally, assorted boxes are loaded on outgoing trucks and shipped to the allotted retail stores.

4.2. Methodology

Challenged with the issue of increasing the efficiency of warehouse operations at the DC, our research group engaged into the development of a model with the goal of understanding the effects that different supply sourcing policies and warehouse personnel usage may bring to the operational and economic performances and to support the company with a viable decision making system at an operational and detailed level.

In particular, the company asked whether the task of item count should be outsourced and about evaluating the extent to which personnel flexibility, obtained through seasonal manpower, may benefit operations performance.

To this end we applied the SD methodology. A few considerations led us to select this simulation methodology rather than other suitable ones, such as Discrete Event Simulation (DES). First, SD appeared to be suited for representing nonlinear processes, such as warehouse operations. Second, the company needed a model to depict the entire warehouse management structure, and SD is considered to be focused on the analysis of systems as a whole, while DES usually models particular processes. Third, the company's request for a tool to support decision making required a system that allows for the analysis of policy options. Finally, decision making requires the ability to understand events that might change model variables. This knowledge is assured by the attention SD gives to feedback, whereas in DES, the parameters are often fixed once entered into the model (Sweetser, 1999).

The process of building the SD model was developed according to the directions given by Lyneis (1998) and was accomplished over a period of six months. First, we worked on understanding, structuring, and analysing the flow of clothing items all of the way through the DC, from receiving to shipment. Information and data were collected and analysed with the help of process stream mapping, interviews with logistic managers and employees, and direct observation of operations.

Then, we developed a quantitative SD model of the warehousing system with stocks, flows, causal feedbacks, and mathematical equations (Sterman, 2000). The understanding of the cause and effect relationships among the system variables clarified the main elements of complexity.

The model was then validated through historical data curve fitting, robustness assessments when confronted with extreme exogenous conditions, and sensitivity analyses associated with random values of variables.

After validation, simulations were run under many case scenarios to capture the impact of different management policies on warehouse activities and inventory levels.

5. The System Dynamics model

5.1. General structure of the warehousing model

The whole SD model of Miroglio's warehouse operations may be decomposed into a few interconnected sub-systems associated with each phase of the logistic flow of items described in Figure 1.

Take in Figure 1

In particular, each process phase is represented by a stock of clothing items flowing out to the successive process step. For example, the stock of unloaded items decreases as clothes flow to either a stock of urgent items or an accumulation of items to be counted, and so forth, throughout the warehouse workflow. Regardless of any sequencing or overlapping, all tasks share the same human resources, and the picking job is mandated by incoming orders.

The model structure also considers the cost of operations, so it is able to represent both time and economic performance metrics.

The model and associated differential equations have been developed using the Vensim® DSS software package by Ventana Systems. The simulations were performed with Euler integration, with one-day time intervals, and a simulation horizon consistent with one season (26 weeks composed of 5 working days).

Because there is no space here for an extensive presentation of the complete system, the following is an overview of the sub-systems of the SD model and a detailed description of the "Count" section, which is the only section directly connected to the decision making process discussed in the next sections. The reader may ask the authors for the complete model and mathematical equations.

5.2. Subsystems overview

The structure of the SD model is as follows. The number of items entering the DC in each time interval is the input flow for the "Unloading" section of the model. This calculates the unloading rate based on the number of items to be unloaded, people assigned to this activity by the "Human Resources" sub-model, and their productivity. A portion of the unloading rate feeds the "Urgent Picking" section of the model, whose aim is to determine the urgent picking rate in a similar way as the "Unloading" sub-model. A second portion of the unloading rate enters the "Count" section, while, as far as the "Inventory" is concerned, the storing rate determines the level of inventory. This, together with confirmed orders, quantifies the required picking workload and, in turn, the ordinary picking rate. Ordinary and urgent picking rates join together in the “Sorting” sub-model to feed the stock of clothing items waiting to be sorted by the automated conveyor. In this case, the sorting rate depends not only on staff productivity but also on the productivity of the automated sorter. Finally, the sorting rate is the input flow to the “Loading” sub-model, which is very similar to the “Unloading” section.

Also, two organisational processes are included into the case model, namely human resources and order management. On the one hand, human resources flow among several stocks of staff devoted to execute different operations, such as unloading, count, picking, etc. At the beginning of simulations, all operators are part of the stock of available staff, while the other stocks are empty.

On the other hand, in the “Orders” sub-model, four input flows represent the incoming orders according to their nature and geographical origin. These form stocks of orders to be fulfilled, whose output flows represent order fulfilment rates calculated taking into account the picking rate evaluated in the related SD sub-model.

5.3. The “Count” section of the model

The task of counting the number of unloaded items is one of the most sophisticated tasks at Miroglio’s warehouse. Non-urgent incoming items undergo a specific process according to the supply source.

The complete “Count” section of the SD model is shown in Figure 2. The following description aims to analyse each specific part of this sub-model.

Take in Figure 2

The representation of the different flows of incoming clothing items is in Figure 3.

Take in Figure 3

Incoming items from the external platform, where items are checked against orders, flow straight to inventory.

The items coming directly from vendors are counted either manually or automatically by way of the same automated sorting conveyor, which is later used for sorting the outgoing boxes. More specifically, items from new or unreliable suppliers are automatically counted, while items from reliable fashionists are manually sample enumerated. If the sample item count is not compliant with the expected quantity, a complete manual count is performed.

The 'Rate of items to automated count' is the rate of items counted by the sorting carousel and is defined according to Equation (1):

Rate of items to automated count = Rate of incoming items – Rate of items to sample count – Rate of incoming items from platform (1)

where:

Rate of items to sample count = Rate of incoming items * % Items from reliable suppliers (2)

Rate of incoming items from platform = Rate of incoming items * % Items from platform (3)

The automated item count process is shown in Figure 4. The sorter counts the full delivery. The operators load items onto the machine; a conveyor passes items under a barcode reader, which registers their model, version, and size. Then the sorting conveyor puts items into boxes, one for each combination of item, version, and size, which are stocked in the storing area.

Take in Figure 4

‘Automated count rate’ is a function of the ‘Work required for automated count’, the actual productivity of staff operating the automated sorter, and the number of staff assigned to automated count. However, because the conveyor also sorts outgoing boxes, the staff must perform both counting and sorting. Thus, the ‘Automated count rate’ is also negatively influenced by the work required for picking items from the carousel, as per Equation (4):

> Automated count rate = IF THEN ELSE (Staff to automated count >Work required for picking/Week, MIN((1- Work required for picking /Staff to automated count) * Actual productivity *Staff to automated count, Work required for automated count* Actual productivity), 0)/Week (4)

Take in Figure 5

Finally, the manual sample count process is diagrammed in Figure 5, where two rates flow out of the ‘Sample count queue’, namely, the ‘Sample count rate’ and ‘Rate of items to re-count’.

On the one hand, the ‘Sample count rate’ includes those items that can be stored after a successful count. This is a function of the number of operators assigned to manual counting and the productivity of staff assigned to the counting (‘Sample count productivity’), which in turn depends on the actual productivity of the staff assigned to manual counting (‘Manual count productivity’), the ‘Sample size’, the maximum productivity of staff taking care of manual count ('Maximum manual count productivity'), and the 'Staff usage' (Equation (5)).

Sample count productivity= IF THEN ELSE (Manual count productivity = 0, Maximum manual count productivity * Staff usage/Sample size, 0) (5)

On the other hand, the 'Rate of items to re-count' is the input flow for the portion of the SD model that depicts the full manual re-count job when the sample count is not successful. This has a similar structure to the previous sections of the model (Figure 6).

Take in Figure 6

5.4. Model validation

The model was refined and validated through historical data curve fitting and robustness and sensitivity analyses.

The curve fitting analysis compares simulated results against historical series of data recorded during the spring/summer 2007 season. This analysis allows for refining the model when large discrepancies arise until an acceptable level of curve fitting is available.

For example, Figure 7 plots the actual curve line of the 'Rate of incoming items' against the simulated results out of the final refined release of the model.

Take in Figure 7

Here, deviations between the two curve lines arise from week 17 to week 20 because the model does not consider a few Italian holidays, and the model fails to take into account the new orders for the coming fall/winter season at week 26 (which is out of the simulation timeframe).

Despite minor discrepancies, these results, together with other curve fitting analyses, suggest that the final release of the model appropriately replicates the real warehousing system. The model also proved to be robust because most of simulations under extreme values of the most important exogenous variables resulted in an acceptable behaviour of the system.

Finally, we performed univariate and multivariate sensitivity analyses (Sterman, 2000) to evaluate probability distributions of relevant outputs, together with their confidence bounds.

For instance, Figure 8 shows the results of the univariate analyses simulating two stocks associated with counting tasks when the exogenous parameter ‘Percentage items from reliable suppliers’ changes randomly out of a uniform distribution between 0% and 70%.

Take in Figure 8

The diagrams show the confidence bounds within which the output values can be found with a probability of 50%, 75%, 95%, and 100%, and demonstrate that the stocks are highly susceptible to changes in the quantity of items that come from reliable supply sources. This means that changing the supply source is a relevant driver of performance and an important factor to consider in making warehousing process improvements.

5.5. Case scenarios and discussion of results

Table 1 reports a short list of performance parameters that are output to the model and are used to quantify the behaviour of the warehousing system when organisational changes are introduced.

Take in Table 1

In particular, with the purpose of supporting the decision making process, the validated SD model was used to assess the effects of potential policies to increase the efficiency of the item count activity. To stress the relationship between warehouse and inventory management, this discussion will first focus on the impacts of different item count strategies. Then staff and economic considerations are provided.

We present two case scenarios. Scenario #1 evaluates the implications of outsourcing the count task by varying the share of items received through the third-party logistic platform from 0% to 100%.

Figure 9 indicates how the average seasonal values of inventory level (a) and the average number of warehouse staff assigned to manual count (b) vary with the fraction of items coming from the logistic platform.

Take in Figure 9

Figure 9(a) shows that inventory levels increase as more of the counting task is outsourced to the logistic platform because of a reduced time spent at the DC on item count. At the same time, with more outsourcing, fewer staff are required to perform the counting job, as shown in Figure 9(b). The square marks represent the current average values of inventory (about 370,000 items) and workforce (4 persons) associated with the share of items currently coming at Miroglio's DC from the logistic platform (30%). The two plots suggest that, if the number of staff is not fixed, the required number of operators is between 2 and 0, depending on the fraction of items coming from the platform. This in turn allows for savings on labour cost without affecting the inventory level significantly.

Scenario #2 focuses on the consequences of changing the percentage of items sourced from reliable suppliers, and thus subjected to sample counting, while keeping constant the current portion (approximately 30%) of items received from the third-party logistic platform. Therefore, the fraction of items from reliable suppliers ranges from 0% to 70%. Figure 10 gives indications on how the average seasonal values of inventory levels (a) and the average number of warehouse staff assigned to manual count (b) vary with the fraction of total items coming from reliable vendors.

Take in Figure 10

Figure 10(a) illustrates that the curve line of average inventory levels has its minimum value associated with a 30% fraction of items from reliable suppliers, with small increases away from this point.

Figure 10(b) reports the straight-linear increase of the number of staff required with the fraction of items sourced from reliable manufacturers. This proves that the larger the reliable source base, the more the staff necessary for the manual count. In turn, this reduces the time for the automated conveyor to support the item count duty and increases the time the sorter can be used for the more appropriate task of sorting outgoing boxes.

Here also the square marks plot the average values of inventory (373,000 items) and workforce (4 persons) associated with the share of items currently sourced from reliable suppliers (40%), as per the first scenario.

The two graphs highlight that, if the number of staff is not fixed, the required number of operators is between 2.6 and 0, depending on the fraction of items from reliable sources. Similarly to the first case scenario, this enables manpower cost savings without remarkable consequences on the level of inventory.

So far, we could examine the operational efficiency brought by changing the supply mix. However, these aspects have to be completed with the economic outcomes of the case scenario simulations.

To this end, as far as Scenario #1 is concerned, Figure 11 presents the total cost of warehouse operations calculated by the simulation at the end of the season as the fraction of items coming from the logistic platform is varied.

Take in Figure 11

The associated regression line shows that savings up to €164,000 can be obtained per season. For example, a 10% increase in the quantity of items coming from the platform would bring savings of approximately €13,000 per season.

Also, the square mark shows that the cost Miroglio currently faces is the greatest. According to these results, if the company changed the way the staff is assigned to count (from a fixed number approach, to the variable one suggested in this paper), about €75,000 per season would be saved, assuming the portion of total items coming from the platform remaining fixed at 30%.

Considering Scenario #2, Figure 12 represents the total cost of warehouse operations calculated by the simulation at the end of the season as the fraction of items coming from reliable suppliers changes. Here it is shown that an increase of one tenth in the portion of items coming from reliable suppliers would bring savings of €10,000 per season. Also in this case, Miroglio currently faces the greatest cost (square mark).

Take in Figure 12

Moreover, the company would also save a relevant amount of money when using flexible human resources, regardless of the fraction of items sourced from reliable vendors. Simulations show that the total cost of warehouse operations is kept at a minimum when both the staff allocation is based on actual work required and the fraction of items from reliable manufacturers equals its maximum value (i.e., 70% of total items). In such a scenario, the expected cost is €921,000, with approximately €106,000 saved per season.

Finally, the simulations also give insights about the opportunity of outsourcing the count task: when all items are set to arrive from the platform, savings would attain €0.04 per item. This unit cost is the maximum additional expense Miroglio may be willing to pay for having the count job performed by a supplier.

Similarly, if all items currently purchased from unreliable suppliers were purchased from reliable sources, €106,000 per season would be saved, which represents a ceiling additional price for compensating vendors for reliability.

All simulation results confirmed mental models of Miroglio’s management.

6. Conclusion

This paper discusses the application of SD to a case study of the detailed warehouse operations of a vertical manufacturer of mass clothing items. This approach has been used to study the relationships linking warehouse with inventory management and to understand the complex behaviour of a DC. In particular, the proposed case study suggests that a more flexible usage of human resources, outsourcing of selected warehouse operations (such as item count), and sourcing from reliable, yet more expensive, manufacturers may result in cost savings, reduced inventory, and shorter warehouse lead-times.

It is also proved that SD is a valuable supporting tool not only for strategic evaluations but also for making decisions and taking managerial actions aimed at improving the performance of detailed warehouse, inventory, and logistics operations. The model can be used as a flight simulator to anticipate any consequences of various policies by leveraging on a few parameters and as a supporting tool for continuous managerial learning resulting from ongoing process feedback.

However, this approach poses limitations in the sense that the application of the proposed model is highly specific to the particular case study on warehouse operations reported (Pegels and Watrous, 2005). Moreover, a SD model gives the current picture of a system, so it must be constantly updated to include the latest organisational changes. Finally, simulations predict behaviours arising from particular case scenarios and assumptions, which require post validation because the best way to assess the responsiveness of a case model is to compare real world performance records.

7. Acknowledgments

This study is part of the Miroglio SC reengineering project performed in conjunction with the research group for Engineering Systems and Logistics of Politecnico di Torino. The authors wish to acknowledge the Miroglio Group and, in particular, Mr. Piero Abellonio, Logistic Director, for his active collaboration, support, and permission to publish this study.

8. References

Akkermans, H. and Dellaert, N. (2005), "The rediscovery of industrial dynamics: the contribution of system dynamics to supply chain management in a dynamic and fragmented world", *System Dynamics Review*, Vol. 21 No. 3, pp. 173-186.

Anderson, E.G. and Morris, D.J. (1999), "A simulation model to study the dynamics in a service-oriented supply chain", paper presented at The 1999 Winter Simulation Conference.

Anderson, E.G. and Morris, D.J. (2000), "A simulation game for service-oriented supply chain management", *Journal of Production and Operations Management*, Vol.9 No.1, pp. 40-55.

Anderson, E.G. Jr., Morrice, D. J. and Lundeen, G. (2005), "The "physics" of capacity and backlog management in service and custom manufacturing supply chains", *System Dynamics Review*, Vol. 21 No.3, pp. 217 – 247.

Ashayeri, J. and Lemmes, L. (2006), "Economic value added of supply chain demand planning: A system dynamics simulation", *Robotics & Computer-Integrated Manufacturing*, Vol. 22 No. 5/6, pp. 550-556.

Baker, P. (2007), "An exploratory framework of the role of inventory and warehousing in international supply chains", *The International Journal of Logistics Management*, Vol. 18 No.1, pp. 64-80.

Bruce, M. and Daly, L. (2006), "Buyer behaviour for fast fashion", *Journal of Fashion Marketing and Management*, Vol. 10 No.3, pp. 329-344.

Cagliano, A.C. (2010), *Understanding Supply Chain Complexity. An Approach Integrating Performance Measurement and System Dynamics*, VDM Verlag Dr. Müller, Germany.

Chandra, C. and Kumar, S. (2000), "An application of a system analysis methodology to manage logistics in a textile supply chain", *Supply Chain Management, An International Journal*, Vol. 5 No. 5, pp. 234-244.

Cristopher, M., Lawson, R. and Peck, H. (2004), "Creating agile supply chains in the fashion industry", *International Journal of Retail & Distribution Management*, Vol. 32 No.8, pp. 367 – 376.

Croson, R. and Donohue, K. (2005), "Upstream versus downstream information and its impact on the bullwhip effect", *System Dynamics Review*, Vol. 21 No.3, pp. 249 – 260.

De Koster, M.B.M. (1998), "Recent developments in warehousing", working paper, Rotterdam School of Management, Erasmus University, Rotterdam.

De Koster, M.B.M. and Warffemius, P.M.J. (2005), "American, Asian and third-party international warehouse operations in Europe. A performance comparison", *International Journal of Operations & Production Management*, Vol. 25 No.8, pp. 762-780.

Faber, N., De Koster, R.B.M. and Van de Velde, S.L. (2002), "Linking warehouse complexity to warehouse planning and control structure", *International Journal of Physical Distribution & Logistics Management*, Vol. 32 No. 5, pp. 381-395.

Fisher, M. and Raman, A. (1996), "Reducing the cost of demand uncertainty through accurate response to early sales", *Operations Research*, Vol.44 No.1, pp.87-99.

Forrester, J.W. (1961), *Industrial Dynamics*, MIT Press, Cambridge, MA.

Frazelle, E.H. (2002), *Supply Chain Strategy: The Logistics of Supply Chain Management*, MacGraw-Hill, New York, NY.

Ghemawat, P. and Nueno, J.L. (2006), "Zara: Fast Fashion", HBS 703-497, Harvard Business School Publishing, Boston, MA, available at: http://harvardbusinessonline.hbsp.harvard.edu (5th March, 2009).

Greasley, A. (2005), "Using system dynamics in a discrete-event simulation study of a manufacturing plant", *International Journal of Operations and Production Management*, Vol. 25 No.6, pp. 534-548.

Größler, A. (2007), "A dynamic view on strategic resources and capabilities applied to an example from the manufacturing strategy literature", *Journal of Manufacturing Technology Management*, Vol. 18 No.3, pp. 250 – 266.

Größler, A., Thun, J. and Milling, P.M. (2008), "System dynamics as a structural theory in operations management", *Production and Operations Management*, Vol. 17 No.3, pp. 373 – 384.

Gunasekaran, A., Marri, H.B. and Menci, F. (1999), "Improving the effectiveness of warehousing operations: a case study", *Industrial Management & Data Systems*, Vol. 99 No.8, pp. 328-339.

Gupta, Y.P. and Gupta, M.C. (1989), "A system dynamics model for a multi-stage multi-line dual-card JIT-kanban system", *International Journal of Production Research*, Vol. 27 No.2, pp. 309-353.

Huq, F., Cutright, K., Jones, V. and Hensler, D.A. (2006), "Simulation study of a two-level warehouse inventory replenishment system", *International Journal of Physical Distribution & Logistics Management*, Vol. 36 No.1, pp. 51-65.

Kumar, S. and Samad Arbi, A. (2008), "Outsourcing strategies for apparel manufacture: a case study", *Journal of Manufacturing Technology Management*, Vol. 19 No.1, pp. 73-91.

Landers, T.L., Cole, M.H., Walker, B. and Kirk, R.W. (2000), "The virtual warehousing concept", *Transportation Research Part E*, Vol. 36 No.2, pp. 115-125.

Lowson, R.H., King, R. and Hunter, N.A. (1999), *Quick response: Managing the supply chain to meet customer demand*, John Wiley & Sons, Hoboken, NJ.

Lyneis, J.M. (1998), "System dynamics for business strategy: a phased approach", *System Dynamics Review,* Vol. 15 No.1, pp.35 – 70.

Maltz, A. and De Horatius, N. (2004), *Warehousing: The Evolution Continues*, Warehousing Education and Research Council, Oak Brook, IL.

Panov, S.A. and Shiryaev, V.I. (2003), "Manufacturing supply chain adaptive management under changing demand conditions", paper presented at the 21st International Conference of the System Dynamics Society, New York, USA.

Pegels, C.C. and Watrous, C. (2005), "Application of the theory of constraints to a bottleneck operation in a manufacturing plant", *Journal of Manufacturing Technology Management*, Vol. 16 No. 3, pp. 302-311.

Petersen II, C.G. (1999), "The impact of routing and storage policies on warehouse efficiency", *International Journal of Operations & Production Management*, Vol. 19 No.10, pp. 1053-1064.

Rafele, C. (2004), "Logistic service measurement: A reference framework", *Journal of Manufacturing Technology Management*, Vol. 15 No. 3, pp.280-290.

Rafele, C. and Cagliano, A.C. (2006), "Performance measurement in supply chain supported by System Dynamics", in Dolgui, A., Morel, G. and Pereira, C. E. (Ed.), *Information Control Problems in Manufacturing*, Elsevier Science, Oxford, UK, pp. 559 – 564.

Rollins, R.P., Porter, K. and Little, D. (2003), "Modelling the changing apparel supply chain", *International Journal of Clothing Science and Technology*, Vol. 15 No.2, pp. 140-156.

Schieritz, N. and Gröβler, A. (2003), "Emergent Structures in Supply Chains-A Study Integrating Agent-Based and System Dynamics Modeling", paper presented at The 36th Annual Hawaii International Conference on System Sciences.

Sterman, J.D. (2000), *Business Dynamics. Systems Thinking and Modeling for a Complex World*, McGraw-Hill, New York, NY.

Sweetser, A. (1999), "A Comparison of System Dynamics (SD) and Discrete Event Simulation (DES)", paper presented at The 17th International Conference of The System Dynamics Society and the 5th Australian & New Zealand Systems Conference, July 20 - 23, Wellington, New Zealand.

White, A.S. (1999), "Management of inventory using control theory", *International Journal of Technology Management*, Vol. 17 No. 7/8, pp. 847-861.

Williams, B.D. and Tokar, T. (2008), “A review of inventory management research in major logistics journals. Themes and future directions”, *The International Journal of Logistics Management*, Vol. 19 No.2, pp. 212-232.

Zomerdijk, L.G. and De Vries, J. (2003), “An organizational perspective on inventory control: Theory and a case study”, *International Journal of Production Economics*, Vol. 81-82, pp. 173-183.

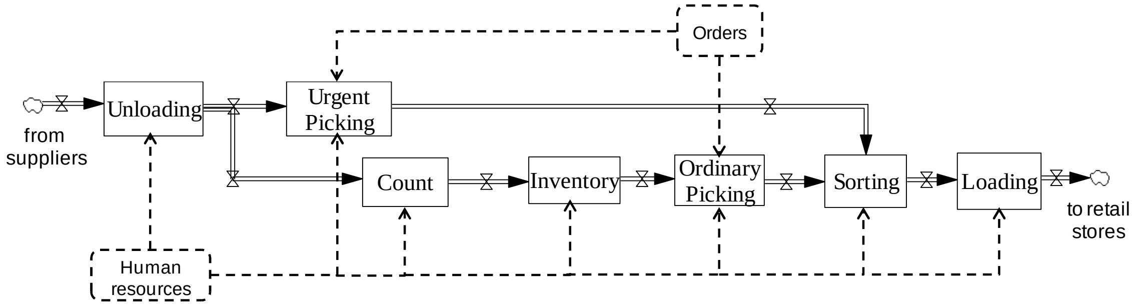


Figure 1. Warehouse operations at Miroglio's distribution centre

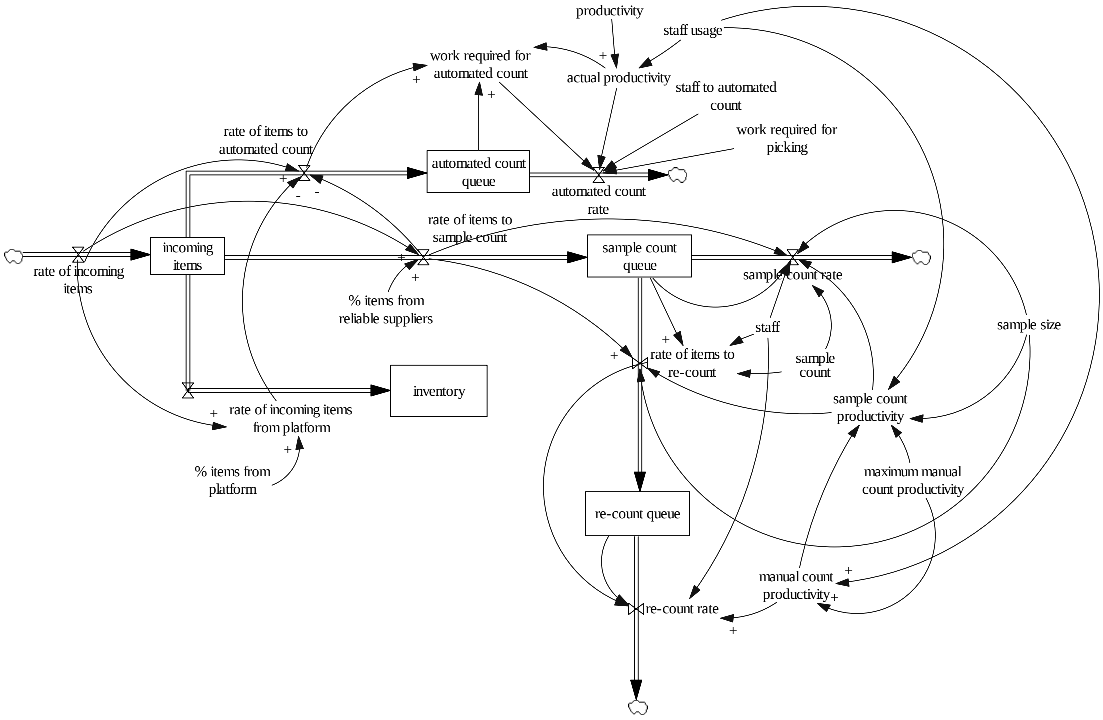


Figure 2. The “Count” section of the SD model

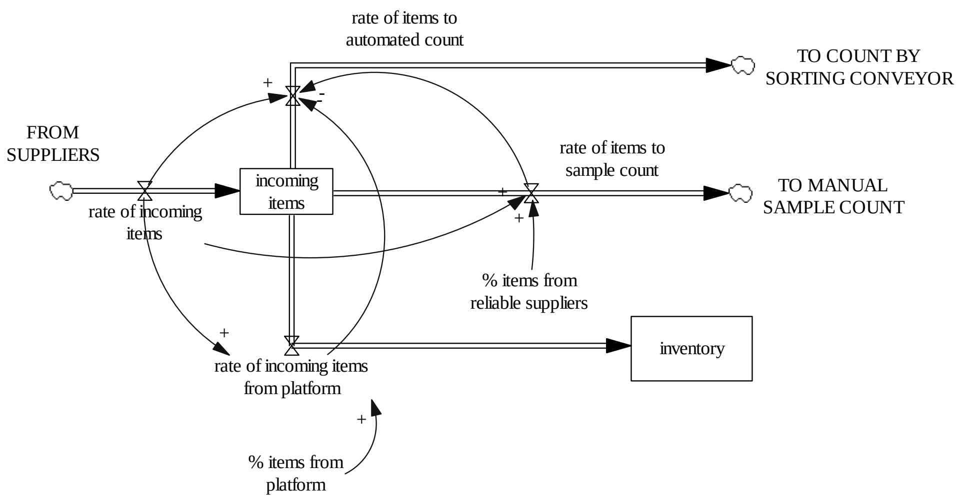


Figure 3. Items flowing into the “Count” section

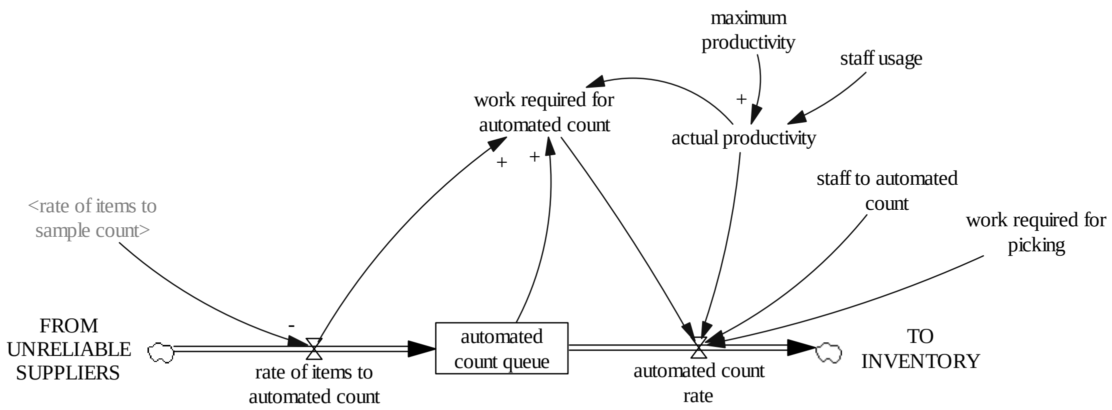


Figure 4. Count by sorting conveyor

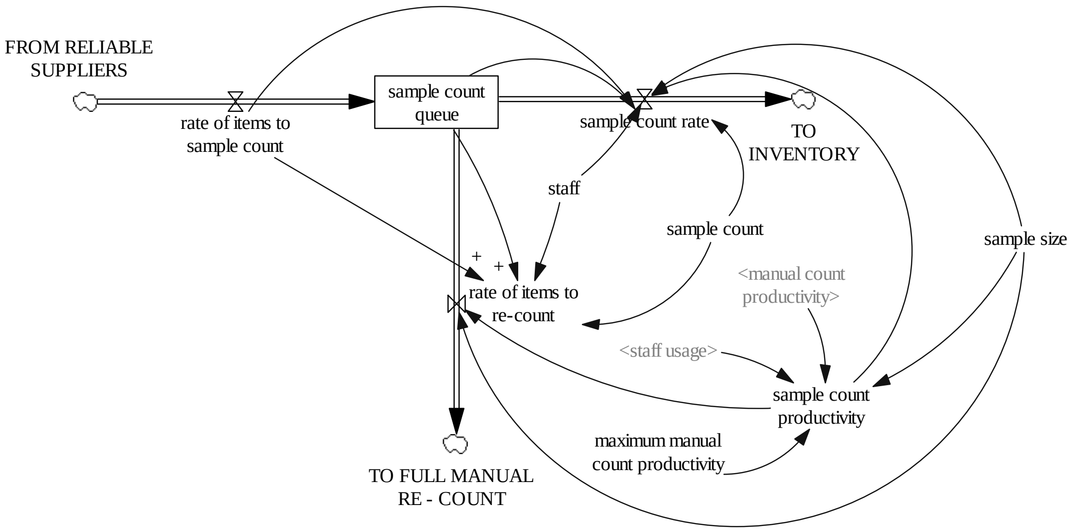


Figure 5. Manual sample count

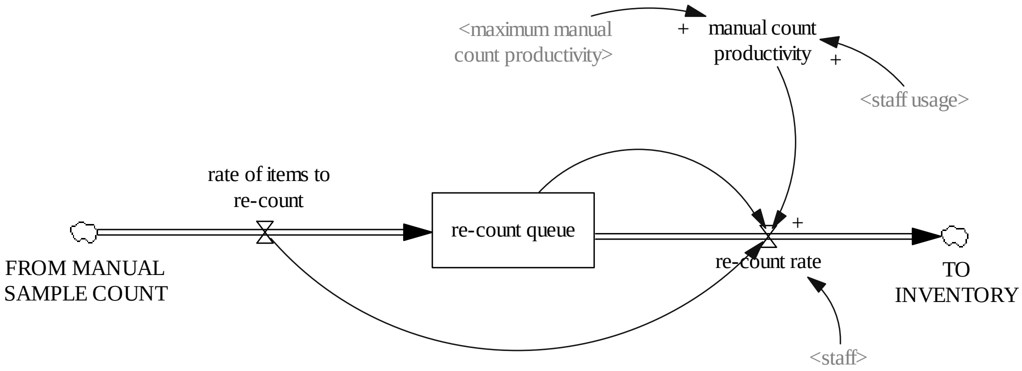


Figure 6. Full manual re-count

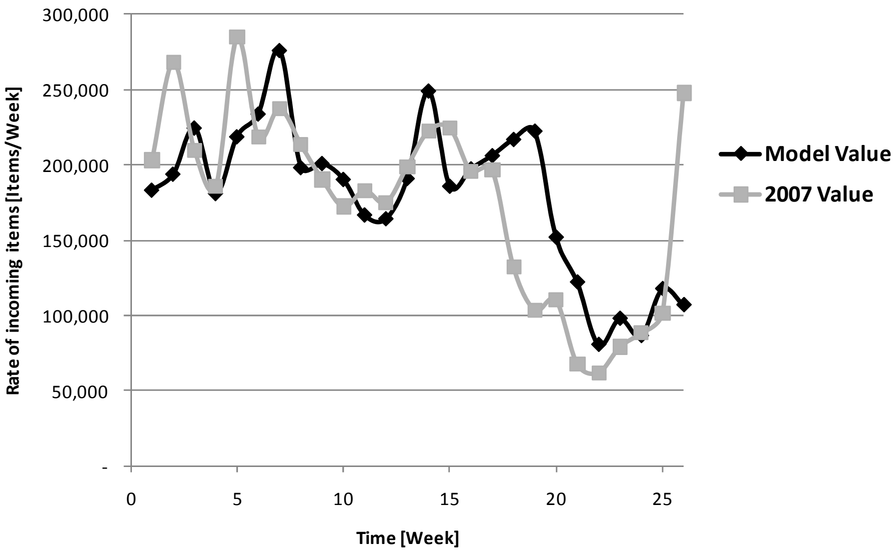


Figure 7. Comparison of simulated vs. real data for the 'Rate of incoming items'

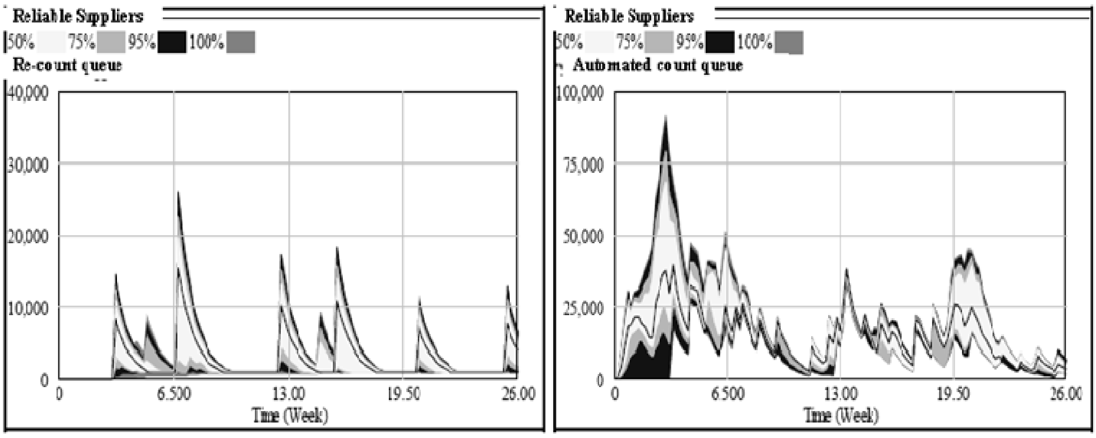
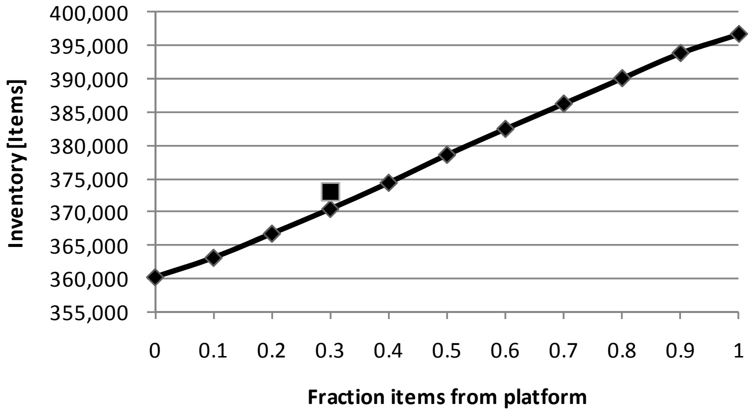
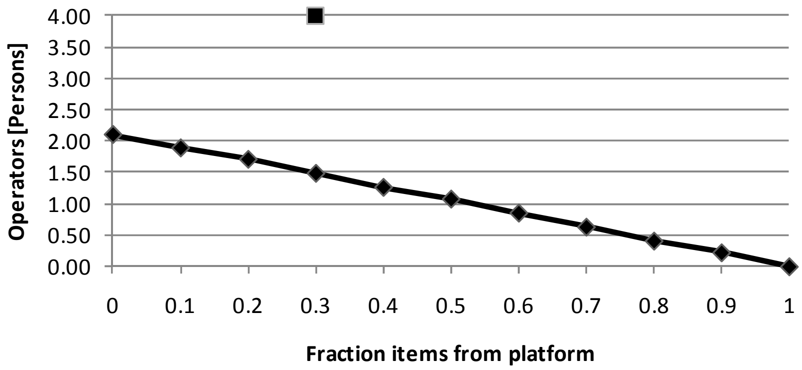


Figure 8. Example of univariate sensitivity analysis

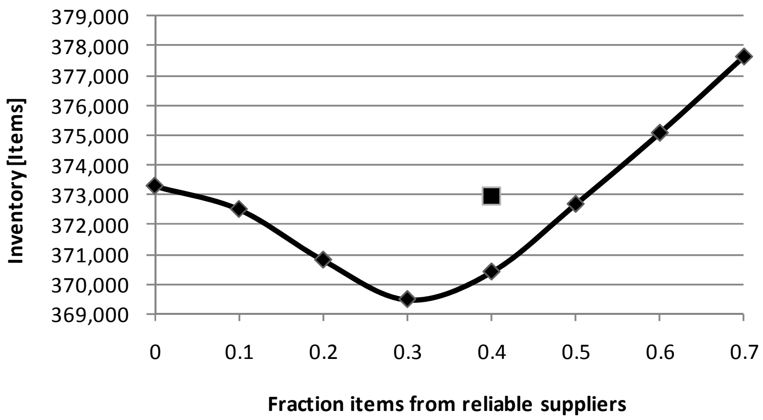


(a) Inventory level

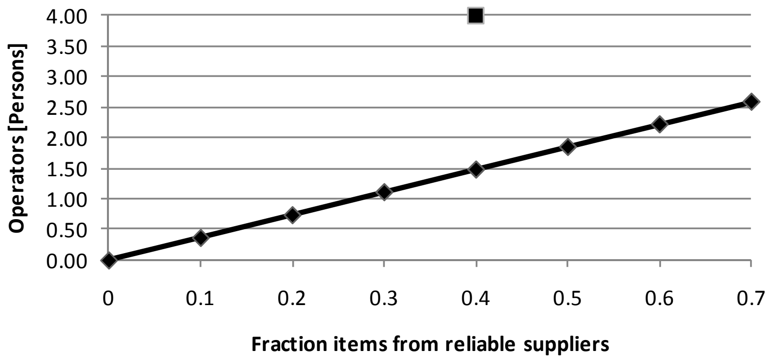


(b) Operators assigned to manual count

Figure 9. Scenario #1



(a) Inventory level



(b) Operators assigned to manual count

Figure 10. Scenario #2

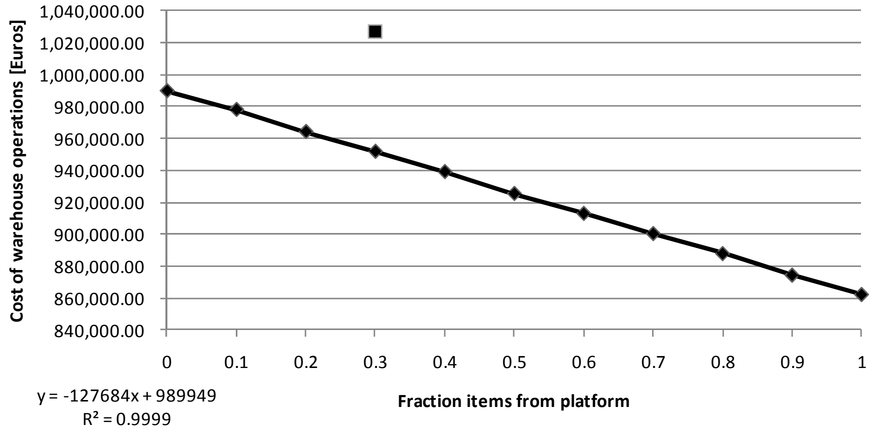


Figure 11. Total cost – Scenario 1, as the fraction of items coming from the platform varies

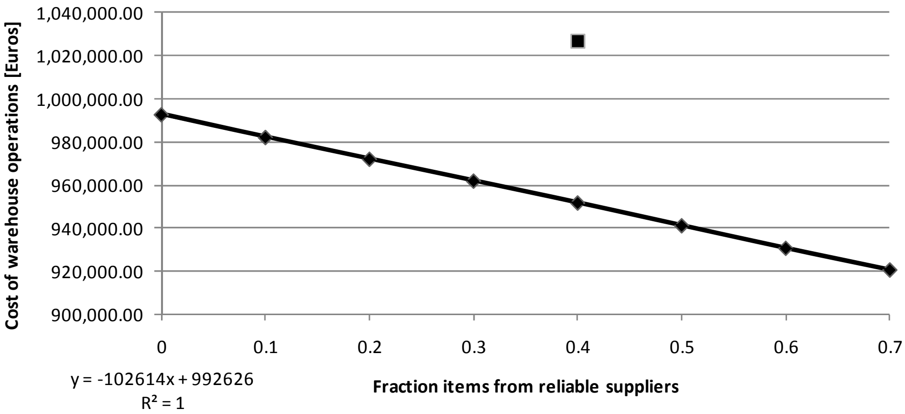


Figure 12. Total cost – Scenario 2, as the fraction of items coming from reliable suppliers varies

Performance parameter	Definition	Units
Sample count queue	Number of incoming items waiting for sample counting	Items
Re-count queue	Number of items waiting for being re-counted in full	Items
Automated count queue	Number of incoming items waiting to be counted by the sorting carousel	Items
Storing queue	Number of items waiting to be stored	Items
Inventory level	Inventory on hand at the DC	Items
Sorting queue	Number of items waiting to be sorted	Items
Operators assigned to manual count	Number of staff assigned to the task of manually counting incoming items	People
Operators assigned to sorting carousel	Number of staff assigned to operate the sorting carousel	People
Total available operators	Number of staff available to perform logistics tasks	People
Total cost	Cost of personnel involved in warehouse operations, calculated over a season	€

Table 1. Main model outputs