A system dynamics model for strategic management of spare parts in closed-loop supply chains

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ABSTRACT

The strategy to recover components from discarded electrical and electronic equipment to obtain spare parts is promising, especially during the final service phase. In that phase, the original product is no longer produced and the sources of new parts are often limited. Controlling those closed-loop supply chains is challenging. Decision makers have to choose when to acquire discarded equipment, when to recover used parts, and when to produce new parts. We developed a generic system dynamics model that provides a test for various proposed policies to control closed-loop supply chains with parts recovery and spare-parts supply.

Keywords: Closed-Loop Supply Chain Management, System Dynamics, Spare parts, Parts recovery

1. INTRODUCTION

The concept of extended product responsibility is getting increasingly important in electronics industry. New laws and regulations oblige original equipment manufacturers (OEM) of electrical and electronic equipment (EEE) to take back and recover their products at the end of their useful lives. A far-reaching attempt at regulation is the European Unions directive on waste electrical and electronic equipment (WEEE). Similar regulations can be found in Japan, Korea, and Switzerland. Therefore, the processes of acquisition/collection, testing/grading, reprocessing and redistribution expand the traditional value chain of producers of EEE and thus closed-loop supply chains (CLSC) appear (Fleischmann 2003). Instruments to plan and control these emerging processes will have to be developed and provided with relevant information. To take advantage of potentials that will arise from closing loops in supply chains, OEMs may try to use product returns as an additional source to replenish materials, components, or products. We concentrate in this paper on the applicability of component recovery strategies to obtain spare parts that are in their final service phase for OEMs of durable EEE. The final service phase begins when the original product is no longer produced. Since producers of EEE must assure the customer of spare-parts supply at least for the average lifetime of the equipment, parts recovery gets promising because the procurement and the manufacturing of spare parts often becomes difficult when they are in their final service phase (Ihde, Merkel, and Hanning 1999) (Fleischmann, van Nunen, and Graeve 2002) (Teunter, and Fortuin 1999) (Hesselbach, Mansour, and Graf 2002).

Thus, at the beginning of the final service phase OEMs frequently predict the entire demand during the remaining service time and manufacture a final lot of that size. Determining final orders accurately is complicated, because a long-term forecast over several years is needed and a number of intangible factors must be considered (Fortuin 1980) (Schulz 1977). In practice, the authors found deviations of about 30-100 per cent over a period of only 30 per cent of the total remaining service period. Especially, the underestimation of spare-parts demand is extremely undesirable, because producers of durable EEE must find alternative sources to maintain spare-parts supply. To meet the demand, firms often have to redesign the specific part. This procedure can be costly, can take several months, and is therefore extremely undesirable for OEMs. Furthermore, the running out of spare parts occurs usually after a considerable time delay after producing the final stock. Because of personnel fluctuation in spare-parts-divisions during that period, the responsibility for spare parts in the final phase is often unclear. Therefore, monitoring of final stocks is often neglected.

It is proposed that parts recovery from discarded equipment is a promising strategy to mitigate the risks of final order strategies, since it raises the operational flexibility of final order strategies (Schröter, and Spengler 2004) (Spengler, and Schröter 2003) (ZVEI 2002) (Teunter, and Fortuin 1999) (Hesselbach, Mansour, and Graf 2002) (Hagen, Iding, and Sudhoff 2000). Hence, adequate closed-loop supply chains have to be designed. The type of a CLSC we considered in this paper is depicted in figure 1.1.

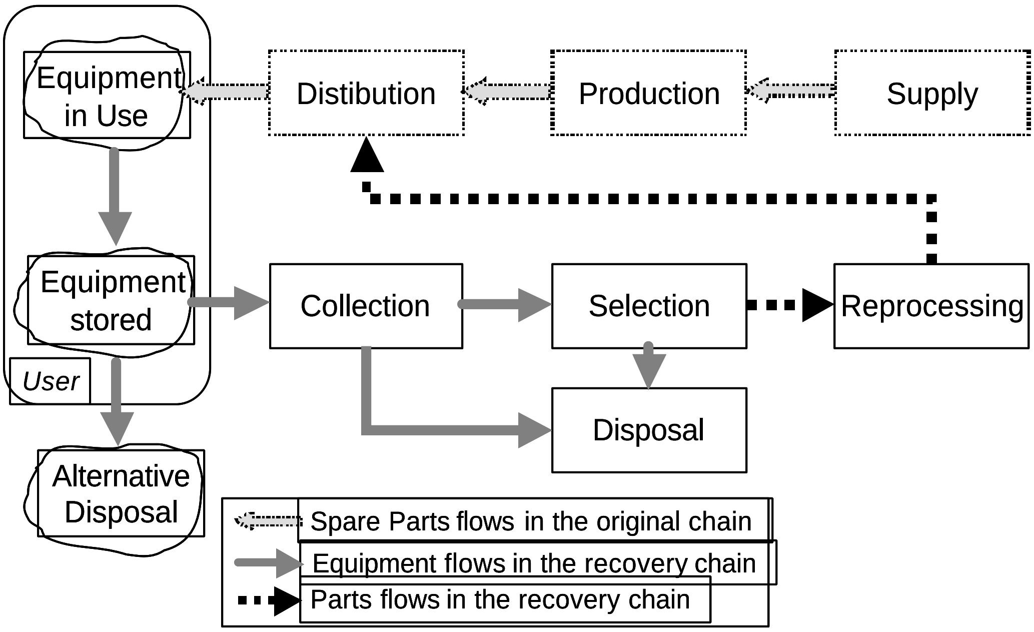

Figure 1.1: Closed-loop supply chain (similar to Fleischmann (Fleischmann 2001))

In such a CLSC reverse logistics and spare parts logistics processes have to be coordinated, which is challenging since the problem is dynamically complex. The aim of the paper is to design robust policies for an integrated management of component recycling and spare-parts supply. To achieve this objective, we developed a strategic-management tool grounded on the theory of system dynamics. The remainder of the paper is organized as follows. In section two, we propose a generic system dynamics model of a closed-loop supply chain for capital goods - for example, medical equipment, copiers, or prepress and printing systems. The model will be used in section three to explain the difficulties that decision makers have in managing parts recovery and spare-parts supply in the final phase, and to test various strategies OEMs of EEE and recovery companies might pursue to improve the functioning of the CLSC. Based on this, conclusions are derived in section four.

2. THE MODEL

In this section, we present a descriptive overview of a generic system dynamics model to analyze and assess various policies to control the CLSC. The model allows us to understand the dynamic behavior of the CLSC from investigating its physical and information flows, its organizational structure, and its decision rules, used within the CLSC.

The model consists of four sectors. Figure 2.1 depicts a model structure overview (Spengler, and Schröter 2003).

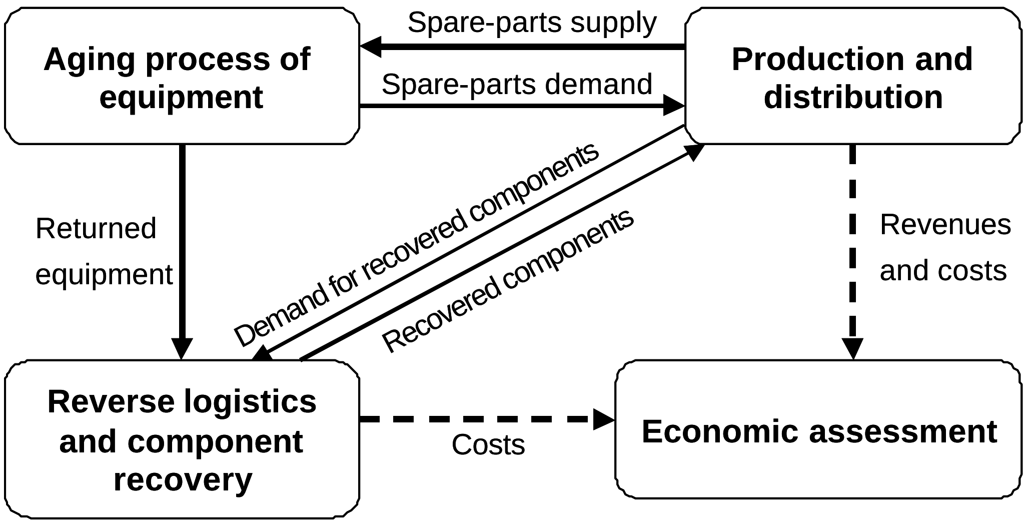

Figure 2.1: Model structure overview

2.1 Aging sector

The number of equipment sold is an exogenous input to the aging sector of the model (equipment sales). Within the aging sector, the equipment in use is modeled as an aging chain, consisting of cohorts for each year of age of the equipment. We refer to Sterman (Sterman 2000) for the details of modeling aging chains and to Zamudio-Ramirez (Zamudio-Ramirez 1996) who uses a similar approach to model an aging chain of automobiles. To consider product returns we modeled obsolescence rates that are the fraction of equipment that will no longer be used, because of fashion, functional or economic obsolescence. We assume that the firm cannot control the obsolescence of equipment. Thus, the obsolescence parameters are exogenous inputs to the model. To consider the fact that users often store obsolete devices instead of directly passing them on to recycling companies, we modeled a "virtual" stock, where the units of obsolete equipment are flowing. Once they are given back to the CLSC, reusable parts can be extracted. Furthermore, users often make use of alternate disposal options, for example passing them to independent recovery companies. This user-behavior causes additional difficulty in estimating product returns.

Since some users may want to keep on using their non-functional equipment after repairing it, we defined age-dependent repair parameters. These parameters determine spare-parts demand.

2.2 Spare-parts supply sector

The spare-parts supply sector models how the firm fulfills spare parts orders, and how it produces and stores spare parts in the final phase. We use the policy structure diagram shown in figure 2.2 to provide an overview of the spare-parts supply, and the reverse logistics and recovery sector of the model. Rounded rectangles represent policies, decision rules, or organizational subunits that are not shown in detail (Sterman 2000).

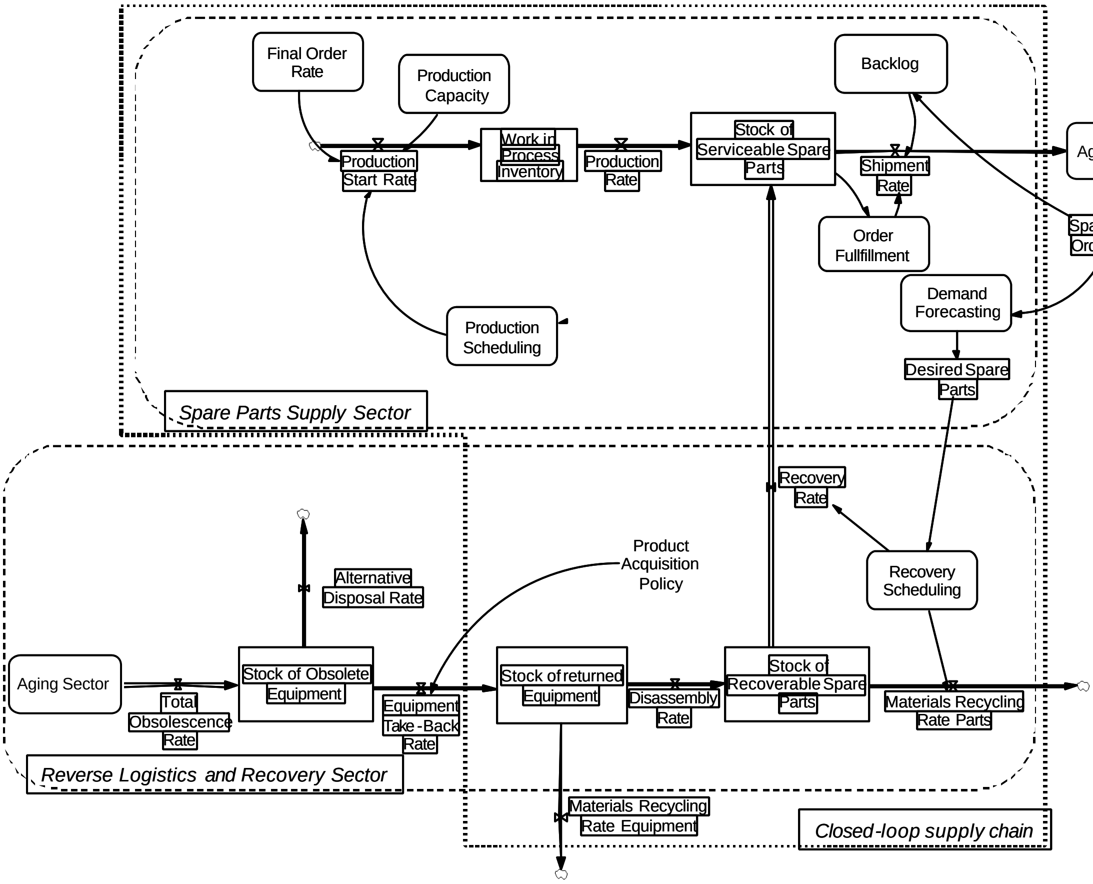

Figure 2.2: Simplified structure of the spare-parts supply sector, and the reverse logistics and recovery sector

A part of the spare-parts supply sector takes pattern from Sterman (Sterman 2000). We expand it by the determination of the final order, and by the coordination with the recovery sector. At the beginning of the final phase, planners determine the final lot size based on the number of primary products sold and the demand forecast. The final lot sizes reflect the decision maker's expectations on the failure rate of the part during the final phase and of the demand for it as a spare part. Because the processes of product return and parts recovery are extremely uncertain, decision makers will not count on recovered parts yet. We assume that they purpose to fulfill the entire spare-parts demand during the final phase by the final stock. In future, this could be different when decision makers can use analogies or time series to estimate more accurately, when and how many used products return and in which condition. Then the firm has to consider the return rate of discarded primary products with recoverable parts over time to take advantage of component recovery by reducing the size of the final order.

Once the demand for a spare part is estimated, the final lot is manufactured with the actual production equipment. Spare parts are stored in the stock of serviceable spare parts. Shortly after the final order is fulfilled, the alternative to produce new spare parts is gone, for example because suppliers discontinued the supply of electronic components, or the firm discarded the production equipment. Thus, the spare parts must be redesigned if the spare-parts demand during the final phase is underestimated.

Customers´ orders for spare parts accumulate in an order backlog until they are processed. We modeled a target delivery delay to consider that orders have to be fulfilled within a certain delivery time to meet customer requirements. In particular, the delivery of spare parts of capital goods is often critical. For medical equipment or similar capital goods, the maximal tolerable machine downtime is a day or two. The firm fills orders from the stock of serviceable spare parts, initially from parts produced in the final lot. If the stock of serviceable spare parts falls below a target value, the firm establishes a desired recovery rate, which is passed on to the recovery sector of the model. Once a redesign of the spare part has become necessary, and as soon as the firm can produce new spare parts, it must coordinate the production process and the recovery process. The difference between the desired recovery rate and the actual possible recovery rate determines the desired production rate. At the end of the final phase, excess spare parts are sent to materials recycling.

OEMs use forecast procedures to determine spare-parts demand, because the lead-time to manufacture, and to deliver spare parts to the customer is higher than the target delivery time. It is assumed, that the producer uses first-order exponential smoothing, which is a realistic model of the forecasting process of spare parts in many firms (Ihde, Merkel, and Hanning 1999).

2.3 Reverse logistics and recovery sector

This sector models how the recovery company takes back discarded products, stores them, disassembles them to recover spare parts, and passes them on for materials recycling. The demand for recovered parts from the spare-parts supply sector is met by depleting the stock of recoverable spare parts. Figure 2.3 depicts an influence diagram, which shows the relationships between the main variables of the spare-parts supply and recovery processes. The starting point of the diagram is the variable "sales of equipment". Minus signs alongside links mean that the dependent variable decreases when the independent variable increases; for example, the higher the "delivery rate" the lower is the "order backlog". Positive signs alongside links means that the dependent variable increases when the independent variable increases; for example, the higher the "production rate", the higher is the "stock of serviceable spare parts". We marked an arrow with double lines, whenever changes of independent variables give effect to dependent variables with considerable delay; for example, the "redesign of the spare part" requires six months.

Disassembling discarded equipment to gain recoverable parts fills the stock of serviceable spare parts. Residuals of the disassembled equipment and used returned equipment, from which the recovery company does not recover parts, are sent to materials recycling. One should consider that it is not possible to recover parts from all of the returned equipment, because of wear and tear. The aging of the equipment in use tends to result in a higher share of non-recoverable parts. Thus, we modeled age-dependent recoverability yields for obsolete equipment. Recovery companies passes on all units of equipment to material recycling if there is no demand of recoverable parts. At the end of the final phase, excess recoverable parts are also sent to materials recycling.

The recovery company obtains its stock of discarded equipment from the discarded products returned out of the stock of obsolete devices held by former users. We modeled two streams of equipment returns. The waste-stream return rate contains the discarded units of equipment that are accepted passively. In comparison, if the firm needs used recoverable parts, it will acquire only that equipment which contains recoverable parts. Hence, it could be expected that the recovery yield rate of that equipment, which is returned market driven, is higher than the units of equipment that are returned waste driven (Guide, and van Wassenhove 2000). The success of the product acquisition policy depends highly on how customer friendly the take-back systems are, or how much the CLSC is willing to pay for a unit of discarded equipment. The more the CLSC is engaged in the take back process of his products, the lower is the quota of obsolete equipment which former users sent to alternative disposal options, for example independent recycling companies. Additionally, it is assumed that it takes more time and more effort to acquire a unit of equipment with recoverable parts the lower the proportion of that equipment to the number of equipment in current use plus the number of units of equipment in the virtual stock of obsolete equipment. The measures to acquire obsolete units of equipment increase the costs for reverse logistics per returned equipment.

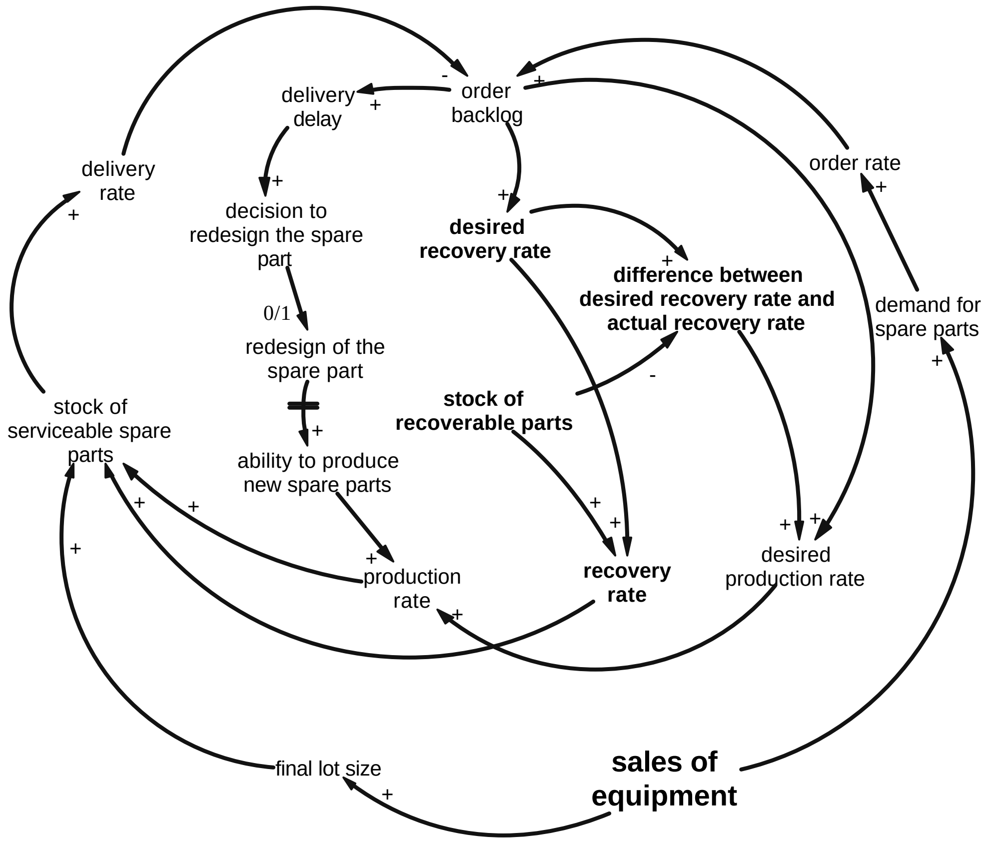

Figure 2.3: Influence diagram of the spare-parts supply and parts recovery processes

The causes and effects, which take place in the reverse logistics and recovery sector, are depicted in the following influence diagram (figure 2.4).

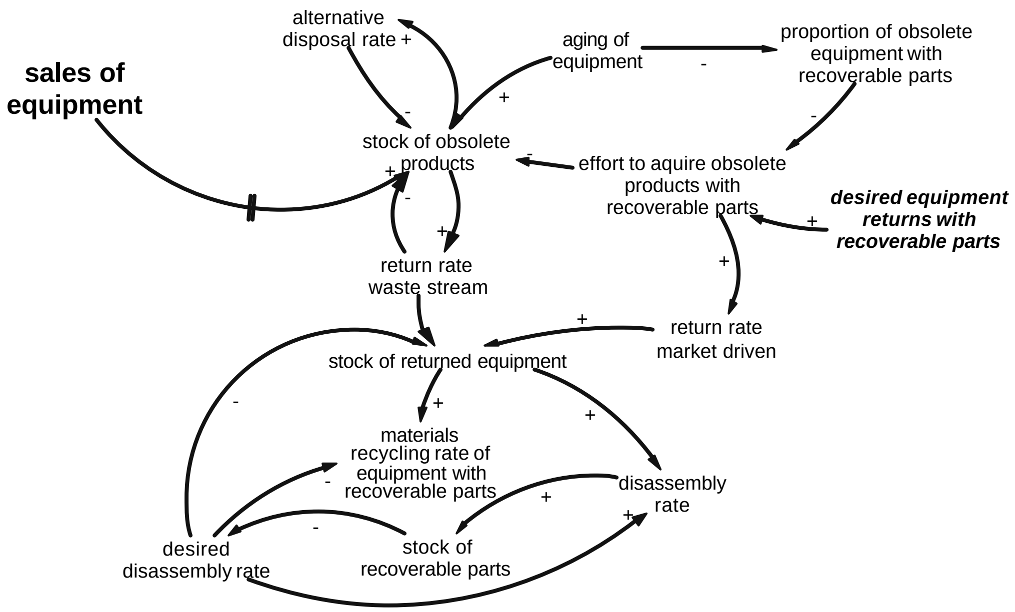

Figure 2.4: Influence diagram of the reverse logistics and recovery sector

2.4 Evaluation sector

Finally, the evaluation sector of the model tracks the costs for production, for reverse logistics, for obsolete equipment acquisition, for disassembling discarded equipment, for recovering components, for material recycling, for storing new and recoverable parts and for redesigning spare parts. With these costs and the revenues from selling spare parts, we can determine the net present value of the simulated policy. Therefore, an adequate target rate must be determined outside the model. In the following, we assume that the costs of the redesign of the spare part and the production costs per part after the redesign are generally higher than recovering parts from discarded equipment and acquiring obsolete equipment from former users. This assumption agrees with the authors' experiences in practice. Additionally, it allows us to focus on the primary purpose of the paper, to design efficient control systems in CLSCs with parts recovery and spare-parts supply.

3. WORKING EXAMPLE

3.1 Base Case

As a working example, we are envisioning an OEM of medical equipment who wants to reorganize its management of spare parts that are in the final phase. The firm often had to redesign spare parts in the past, because its final stocks were not sufficient. Additionally, the firm usually started the redesign of the spare part too late and so customers had to wait for their spare parts. The firm operates a waste driven system to fulfill environmental law requirements, but it is not engaged in using recovered parts from discarded equipment as spare parts until now. We applied the model to a typical product of that firm. The firm produced 3,666 pieces of that equipment during 30 months. After it stopped selling that product, it must guarantee a supply of spare parts for nine years (138 months). The target delay between the order of a customer and delivery is two days. We assume that when the primary product fails, repairing it requires one piece of a specific spare part. The entire spare-parts demand in the final phase amounts to 3,171 parts. The age-dependent obsolescence parameters go up constantly from 0.05 per cent to 67 per cent. The age-dependent repair parameters cut down continually from 98 per cent to 18 per cent.

To focus on the system behavior in the final phase, the initial inventory of the serviceable spare part matches the spare-parts demand that occurs until the beginning of the final phase. The initial parts production capacity is 300 parts per month until the final lot is produced. If a redesign of the spare part becomes necessary, the assumed production capacity is set to 100 parts per month. In average, the OEM needs one month to become aware of a spare part out-of-stock situation. Then, it requires six months to redesign the spare part. To study the dynamic behavior of the spare-parts-supply system when the firm underestimated spare-parts demand, we cut the optimal final lot size (the entire spare-parts demand during the final phase) by about 20 per cent. Figure 3.1 depicts the dynamic behavior of the main flows. The firm starts to produce the final order after the 21st month, to be able to discontinue the production of the part along with the cessation of the equipment. After the 100th month, the final stock is depleted and spare parts orders accumulate in the order backlog. Since the service phase lasts until the 138th month, the firm has to redesign the spare part, which lasts 12 months. Customers have to wait several months before they can use their equipment again, and the firm has to indemnify the customers, for instance by making another piece of equipment with similar functions available to the customer. Costs accrue through the measures of compensation and the redesign of the spare part and reduce the net present value considerably. Since the firm does not recover parts, it passes on discarded equipment directly to material recycling. The firm's waste driven system achieves a return rate of 20 per cent of the obsolete equipment that is former users pass on 80 per cent of their obsolete equipment to alternative disposal options.

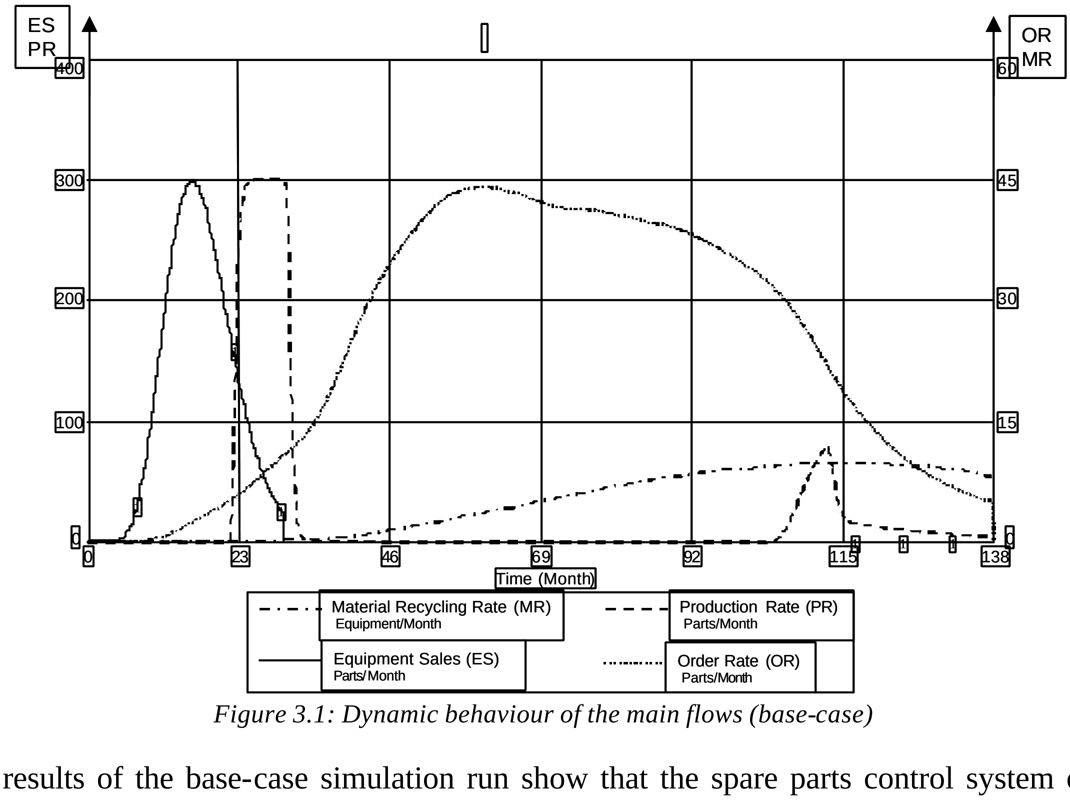

Figure 3.1: Dynamic behaviour of the main flows (base-case)

The results of the base-case simulation run show that the spare parts control system of the firm is inadequately designed. After the firm produced the final lot, there is no other option to response to shortages, than to redesign the spare part. Since the final stock is inadequately monitored, the redesign starts too late to avoid high order backlogs for a long time. In the next sections, we explore modifications of the control system and include the option to recover parts from discarded equipment.

The primary purpose of the study is to raise the robustness of the management control system, and thereby to improve the performance of the CLSC. The system is assumed robust, if an underestimation of demand does not necessarily result in a redesign of the spare part, which is the worst case. Thus, we investigate strategies with regard to the maximum allowable error in forecasting the entire spare-parts demand.

Considering used parts as an additional option for managing spare parts in the final phase the firm has to incorporate the fact that during the final phase the maximum achievable number of recoverable parts decreases permanently. The age-dependent recoverability yields diminish from 92 per cent to 17 per cent for obsolete equipment.

Furthermore, it is assumed that only 20 per cent of the obsolete units of equipment are returned to the CLSC, except the firm acquires obsolete units of equipment in an active way.

3.2 Non-robust policies

In-depth-simulation studies show that reactive policies are not robust. Reactive policies are characterized by the OEMs behavior not to react to shortages in advance. The OEM gains recoverable parts from its waste-stream system not until orders accumulate in the order backlog. Even the OEMs approach to compensate shortages by acquiring obsolete units of equipment with recoverable parts actively to increase the product returns of the waste-stream system is not successful. A better performance of the policy is restricted by the late start to acquire units of obsolete equipment if the final stock size is not enough. Because it requires too much time to acquire and return the units of equipment with recoverable parts, orders begin already to cumulate in the backlog and cause the delivery delay to rise.

3.3 Systemwide-inventory policy

What is required is to initiate the acquisition of units of equipment with recoverable parts early enough, so that the needed parts are in place by the time the final-order stock is depleted. Additionally the redesign of the spare part has to be set off early enough to avoid that the delivery delay rises above the target delivery delay. To cope with those requirements, it seems to be necessary to implement a forecasting procedure within the control management system. Coyle defines "forecasting as the act of giving advance warning in sufficient time for beneficial action to be taken."((Coyle 1978) pp. 237) The variable that has to be forecasted is the systemwide-inventory of parts. The systemwide parts inventory equals the stock of serviceable spare parts minus the order backlog. We integrate forecast procedures into the model that are based on double exponential smoothing, one of the most common methods used in spare-parts management (Ihde, Merkel, and Hanning 1999).

Whenever the systemwide-inventory is forecasted to be depleted, the CLSC has to start to acquire obsolete equipment or to redesign the spare part. Since the recovery of parts is preferred in comparison to the spare part redesign, the forecast horizon of the forecast procedure, which determines the beginning of the acquisition of obsolete units of equipment, has to be sufficiently longer than the forecast horizon of the forecast procedure, which determines the redesign of the spare part. To determine the redesign of the spare part, a forecast horizon of six months, the time needed to redesign the spare part, has been chosen. The forecast horizon to determine the acquisition of obsolete equipment has been set to twelve months. As soon as the CLSC begins to actively collect units of obsolete equipment, the computation of the systemwide-inventory is modified. The systemwide-inventory of parts then equals the inventory of serviceable spare parts plus the inventory of recoverable parts plus the actual recovery yield rate multiplied with the stock of returned equipment minus the order backlog. Thereby, the systemwide-inventory will be larger, and the probability that a redesign will be necessary is lower.

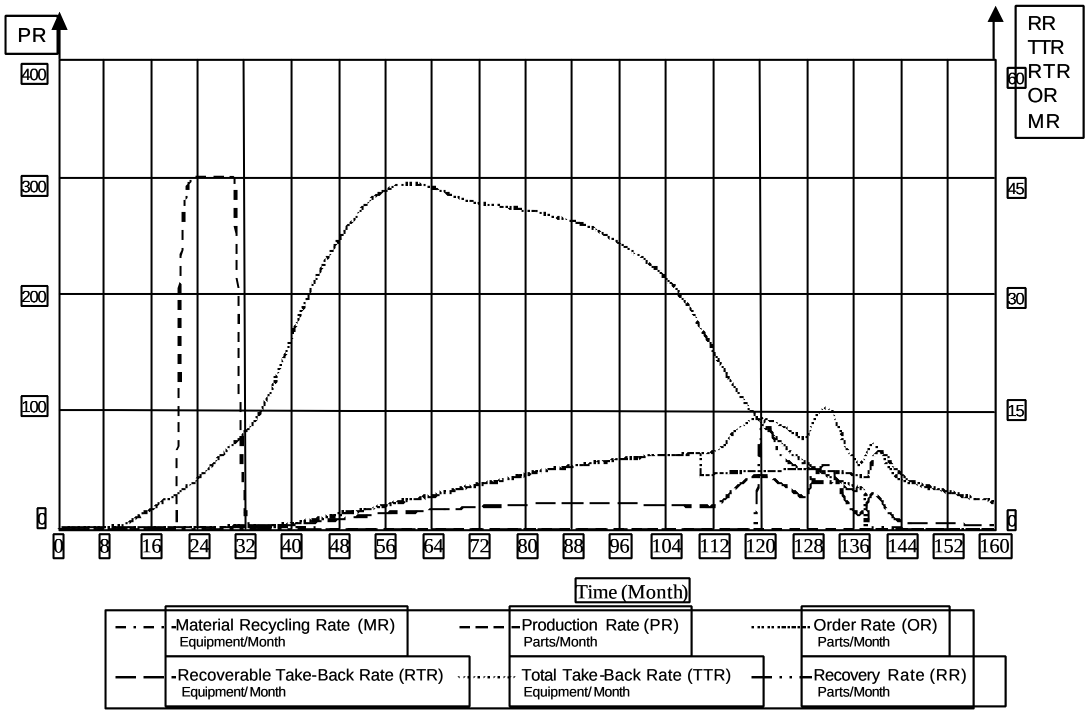

Figure 3.2: Simulation run of the systemwide-inventory policy

The systemwide-inventory policy is more robust in comparison to the reactive policies we have mentioned before, because it allows an underestimation of the spare-parts demand during the final phase by about four per cent.

Figure 3.2 depicts the dynamic behavior of the main flows of the systemwide-inventory policy within a simulation run where the entire spare-parts demand in the final phase has been underestimated by about four per cent. The CLSC forecasts an out of stock situation at the 110th month. Then, it begins to acquire obsolete units of equipment and the material recycling of recoverable parts is stopped. Since spare-parts demand forecast errors amount often up to 10 per cent and more, the results of the systemwide-inventory policy are not sufficient.

3.4 Early-warning-system policy

Another way, which seems to be promising, is to combine the systemwide-inventory policy with an early warning system. Therefore, decision makers, who determine final orders, have to set a schedule how they believe the systemwide-inventory will change over time during the final phase. During the final phase decision makers have to compare the planned schedule of the systemwide-inventory with the actual schedule of the systemwide-inventory continually. Thereby, it will be possible to start to acquire obsolete equipment as soon as there is an obvious risk, that the final stock will not be sufficient to fulfill the entire spare-parts demand during the final phase. The firm needs one month to initiate measures to close the gap between the planned systemwide-inventory and the actual systemwide-inventory.

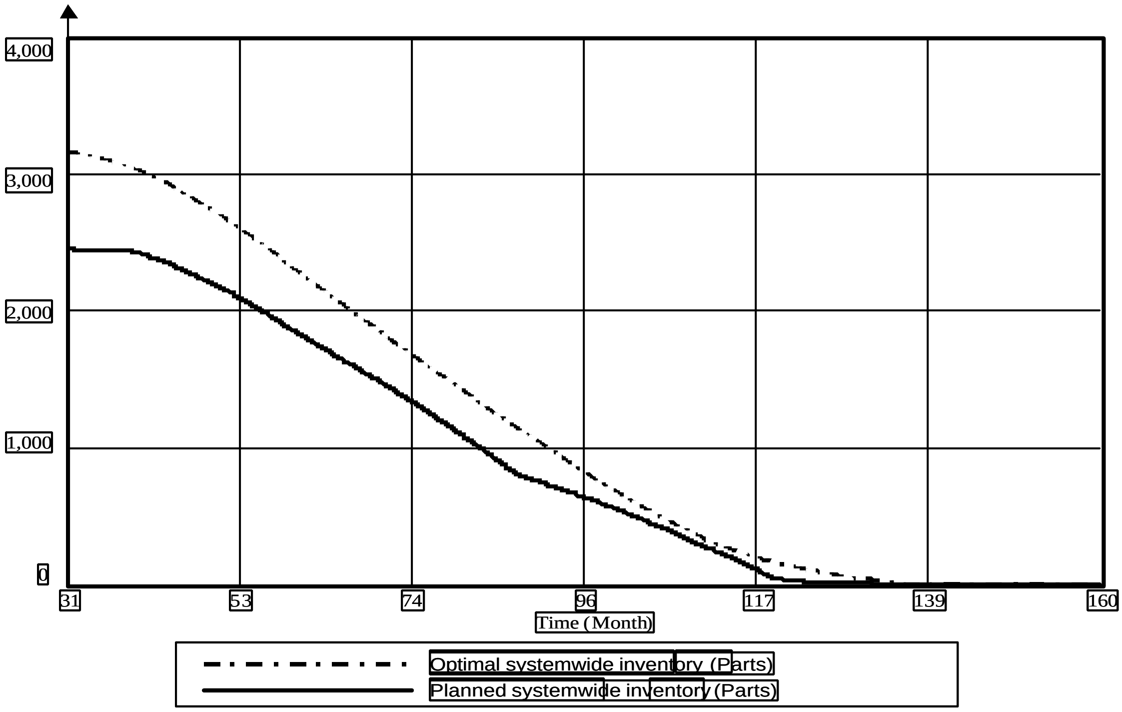

Figure 3.3: Planned and optimal systemwide-inventory within a simulation run of the early-warning- system policy

Figure 3.3 shows the different behavior between a planned schedule of the systemwide-inventory when decision makers underestimate spare-parts demand by about 24 per cent and the optimal schedule of the systemwide-inventory.

Figure 3.4 depicts the result of the simulation run with the given schedule. Even an underestimation of 24 per cent does not result in a spare parts redesign. The main reason is that there is already a difference between the planned systemwide-inventory and the actual systemwide-inventory near the beginning of the final phase. Therefore, the CLSC starts to acquire obsolete equipment and stop the material recycling of units of equipment with recoverable parts very early. Thus, in this case, the early-warning-system policy is very robust.

The use of the early-warning-system policy is the more robust the more the decision maker underestimates spare-parts demand at the beginning of the final phase, because it causes the firm to acquires more units of equipments with recoverable parts.

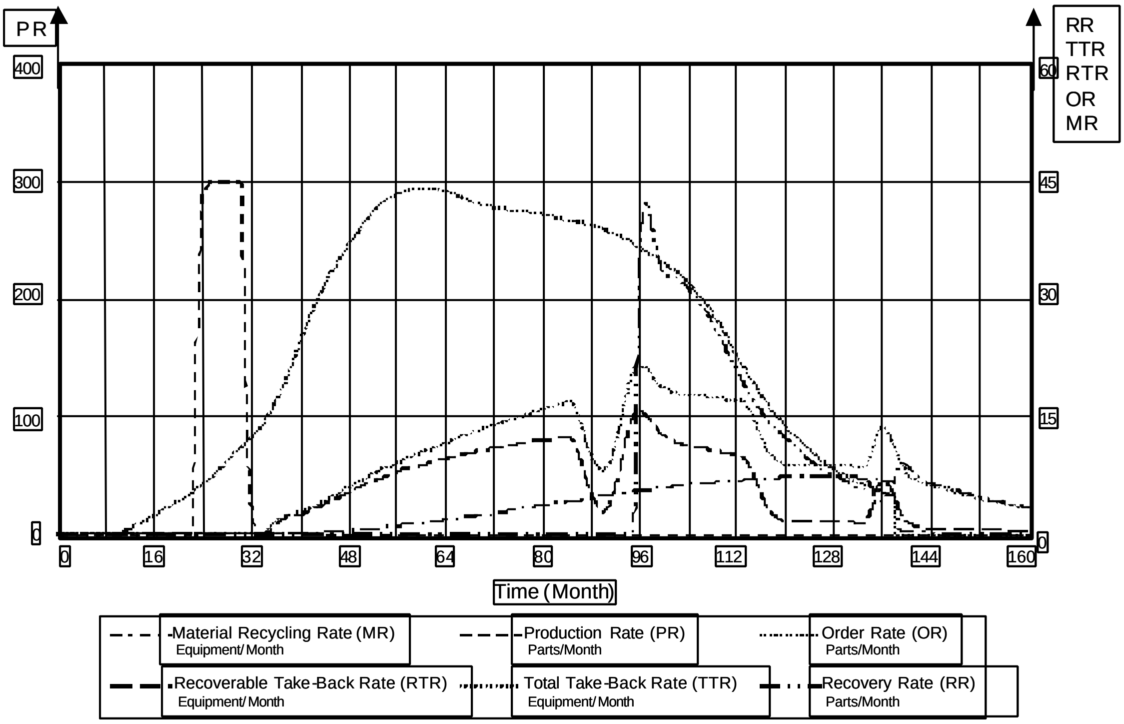

Figure 3.4: Simulation run of the early-warning- system policy

4. CONCLUSIONS

We presented the development of a system dynamics model for designing control management systems within CLSCs with parts recovery and spare-parts supply. The model allows decision makers to study the cause and effects, which takes places in a closed-loop supply chain. We take into account different forms of product take back (active product acquisition and waste stream), and different policies such as, when to stop sending recoverable parts to materials recycling, when to acquire units of equipment with recoverable parts and when to begin to redesign a spare part. Considering the results of section 3.4, it seems to be necessary to strengthen the monitoring of final stocks as well as the stocks of recoverable parts within closed-loop supply chains. Therefore, it is necessary to improve the information exchange between producers of EEE, who have to provide spare parts and recovery companies that are involved in the take-back and recovery process of the producer's goods (Spengler, and Stölting 2003).

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Coyle, R. G. 1978. *Management system dynamics*. Chichester: Wiley.

Fleischmann, Moritz, Nunen, Jo van, and Ben Graeve. 2002. *Integrating closed-loop supply chains and spare parts management at IBM*. Rotterdam: ERIM.

Fleischmann, Moritz. "Reverse logistics networks structures and design." *Business Aspects of Closed-Loop Supply Chains*. Ed. V. Daniel, R. Guide, and Van Wassenhove, Luk N. Pittsburg (USA): Carnegie Mellon

University Press, 2003.
Fleischmann, Moritz. 2001. *Quantitative models for reverse logistics*. Berlin: Springer.
Fortuin, Leonard. 1980. The all-time requirements of spare parts for service after sales - theoretical analysis and practical results. *International journal of operations and production management* 1 (1):59-69.
Guide, V.D.R. Jr., and L.N. van Wassenhove. 2000. Managing product returns for remanufacturing. *Production and Operations Management* 10 (2):142-155.
Hagen, M., Iding, M., and H. Sudhoff. "Lösungsansätze zur Sicherstellung der Nachserienversorgung in der Automobilelektronik." *Elektronik im Kraftfahrzeug*. Ed. Gesellschaft Fahrzeug- und Verkehrstechnik. VDI Berichte. Düsseldorf: VDI-Verl., 2000. 953-978.
Hesselbach, Jürgen, Mansour, Markus, and René Graf. "Erweitertes Supply Chain Management durch ganzheitliches Ersatzteilmanagement." *Logistikplanung und -management: 8. Magdeburger Logistik-Tagung, Magdeburg, 14./15. November 2002*. Ed. M. Schenk, and Ziems, D., Inderfurth, K. . 2002. 225-246.
Ihde, Gösta B., Merkel, Helmut, and Ralf Hanning. 1999. *Ersatzteillogistik: theoretische Grundlagen und praktische Handhabung*. München: Huss.
Schröter, Marcus, and Thomas Spengler. 2004. Designing control management systems for parts recovery and spare parts management in the final phase within closed-loop supply chains. *International journal of integrated supply management* 1 (2):158-179.
Schulz, Ekkehard. 1977. *Grundlagen zur Planung von Ersatzteilfertigungen*. Mainz: Krausskopf.
Spengler, Thomas, and Marcus Schröter. 2003. Strategic management of spare parts in closed-loop supply chains - a system dynamics approach. *Interfaces* 33 (6).
Spengler, Thomas, and Wiebke Stölting. "Recycling-oriented information management in closed loop supply chains in the electrical and electronic equipment industry." *Strategy and organization in supply chains*. Ed. S. Seuring, M. Müller, M. Goldbach, and Schneidewind, U. Heidelberg: Physica-Verl., 2003. 353-368.
Sterman, John D. 2000. *Business dynamics: systems thinking and modeling for a complex world*. Boston: Irwin/McGraw-Hill.
Teunter, Ruud H., and Leonard Fortuin. 1999. End-of-life service. *International journal of production economics* 59 (1-3):487-498.
ZVEI. 2002. *Langzeitversorgung der Automobilindustrie mit elektronischen Baugruppen*. Frankfurt am Main.
Zamudio-Ramirez, Pavel. 1996. *The Economics of Automobile Recycling*. Cambridge.