Planning of Operations in Product Recovery Centers Using Linear Programming

VANEGAS M., SELIGER G.
Department Assembly Technology and Factory Management
Berlin University of Technology, Institute for Machine Tools and Factory Management
Pascalstrasse 8 – 9, D – 10587 Berlin
GERMANY
http://www.mf.tu-berlin.de/

Abstract: In the frame of a sustainable cycle economy, product and component reuse is a good option for achieving higher product utilization with fewer resources. Business models have been developed for collecting, recovering and reselling Information Technology (IT) equipment in Europe. Product recovery centers are in charge of taking back used IT equipment and, depending on product conditions, deciding whether the product shall be refurbished and resold or has to be disassembled in order to recover components and separate materials. Addressing the stochastic nature of quantity, timing and quality of returned products as well as demand and price of remarketing products and components; it is required an efficient planning of operations in recovery centers.
Initially this paper analyzes existing product recovery centers and their activities, described in a generic model. Secondly, a Linear Programming Model (LP-Model) is developed and tested to assign the optimal number of products to each working area: recovery, disassembly to components retrieval and disassembly to material classification. The LP-Model is solved using the program AIMMS™ and considering real data from a recovery center located in Germany. The results of the LP-Model are implemented in a discrete-event simulation model built in the software eM-Plant™. The simulation model includes additional stochastic factors such as changes in failure rate of products and efficiency of manual working stations. The simulation model enables to measure the recovery center performance.

Key-Words: Product recovery center, planning of operations, linear programming, simulation, IT-equipment, End-of-Use (EOU), End-of-Life (EOL).

1 Introduction

Information Technology (IT) equipment such as personal computers, notebooks and printers have reduced drastically their life cycle duration due to accelerated technological development. It is predicted that in the next three years, individuals and organizations worldwide will replace more than 400 million computers [1]. This event opens up opportunities for reusing complete units and components in further life cycles as well as recycling materials to be incorporated again as raw materials in the cycle economy.

Parallel to this phenomenon, raised environmental awareness and improved legal frameworks (such as the European directive on waste of electrical and electronic equipment (WEEE) [2]), are drawing more attention to the proper management of electrical and electronic products End-of-Use (EOU) and End-of-Life (EOL).

Business models in the area of collecting, recovering and reselling IT-equipment in Germany are presented and analyzed. Based on the activities carried out in the recovering centers, a Linear Programming Model is proposed in order to assist the planning of its operations. The objective of the approach presented in this paper is to support the cost optimal assignment of recovery and disassembly tasks, considering demand of reused product and components, failure rates of products and components and available working and storage capacity.

2 Life Cycle of a Product

The Comet Circle™ describes the life cycle of a product, from raw material suppliers to production and, through sales, to customer (user). This is the traditional supply chain. During a use phase, product life duration is extended by maintenance. Afterwards, products are collected and, by reuse of products, components and materials recycling, resources utilized in a product are re-circulated in a cycle economy (Fig.1).

Not all products and product components are worn-out at the end of a product usage phase. This feature provides a possibility for a second usage phase prior to material recycling. The return of products and materials makes necessary the synchronization of different activities and cooperation among companies. Products have to be collected after a use phase, processed and, subsequently, properly disposed. Proper disposal includes the possibility of reusing products and components in good conditions, recycling materials and safely disposing hazardous substances. These activities define the operation of recycling networks.

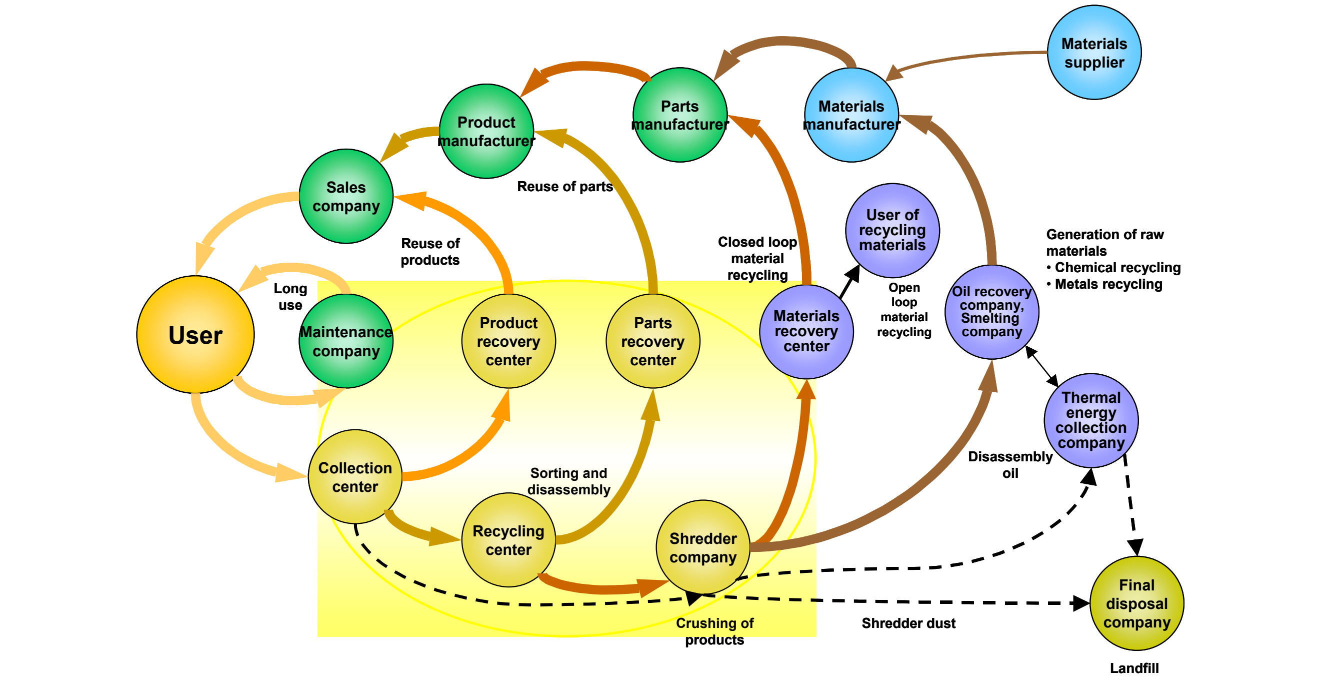


Fig.1 Concept for realizing a society that re-circulates resources: The Comet Circle[TM] – ©1994 Ricoh [3]

In the specific case of IT equipments, they tend to be used for a period of time that is markedly shorter than their technical life. Therefore, their potential to be resold in a secondary market is higher than with other electrical and electronic equipments (e.g. white appliances). The basic approach is to avoid, reduce or adequately dispose electrical and electronic used appliances with the goal of increasing the use productivity of resources already involved in the production of existing equipments.

2.1 Recycling Networks

Basic activities of recycling networks include retrieval of products; treatment processing (e.g. disassembly); distribution of reusable products, components and recyclable materials; and disposal of remaining parts and hazardous components (Fig.2) [4].

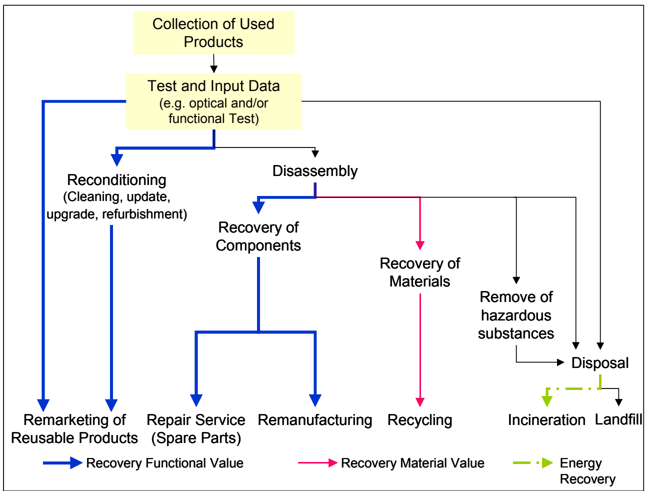


Fig.2 Basic recycling network activities

Operations of a recycling network are characterized by high variability of condition, quantity and timing of returned products, uncertainties in the disassembly process and demand for recovered parts. Moreover, the high variety of product types increases the complexity in the operation of the system.

An essential part of a recycling network is a product recovery center. Their responsibilities include the retrieval of used equipment and, depending on product physical and technical conditions, the decision whether the product shall be refurbished and resold or has to be disassembled in order to recover components and separate materials. This paper concentrates on the activities carried out at a recovery center. Recovery center activities can be organized by Original Equipment Manufacturers (OEM) or by independent companies.

2.2 Recovery Activities Organized by OEM

In the last few years companies in the IT-equipment industry like Fujitsu Siemens Computers GmbH, Hewlett Packard, and Dell have been designing and developing recovery and recycling systems for their used products [5], [6], [7]. They have established take-back and recycling networks in different ways according to their needs and capacities.

The recovery and recycling systems organized by the manufacturers are services for business customers and private end-users. This service allows taking back used products of their brand and at the same time motivating the customer to buy new products.

Reused products are sold by the OEM taking advantages of the brand image and with the same warranty conditions that for new products. However, the OEM is responsible for taking back any kind of product of its brand without considering their condition. If the product is in good condition, the customer can get some monetary retribution and the OEM will be able to resell the product; but if the product is in bad condition, the OEM has to take back and dispose it appropriately, regardless of the incurred costs.

Recovery activities organized by OEM have the advantage of knowing product design, components and materials. This information facilitates the disassembly and recycling. Moreover, taking back used products opens the possibility of getting spare parts as a result of their dismantling. Repair shops can share the same information system with the recovery centers in order to set the demand of spare parts.

2.3 Recovery Activities Organized by Independent Companies

Recovery activities carried out by external companies, for example the firma Flection [8], are focused on buying products with high reutilization rates and potential market demand with the objective of checking, refurbishing and reselling them. Usually, an independent company buys used IT-equipment from leasing companies and enterprises. Leased products are used normally two to three years before the user has the possibility either to return the product to the leasing company or to buy it.

Recovery companies negotiate with the leasing (in this case the supplier) the acquisition price of used products without knowing the condition of the products in advance. Instability in product supply and secondary market demand require a strong and competitive commercial and marketing department in order to guarantee success.

3 Planning of Operations in Recovery Centers

Operations carried out in a recovery center shall be planned through a cost optimal assignment of recovery and disassembly tasks considering supply and demand of reusable products and components, failure rates and available working and storage capacity.

3.1 Modeling the System

Products arrive at the recovery center where they are first registered. Transport and purchasing product costs are considered as acquisition costs. Depending on demand and recovery center processing and storage capacities, products are assigned to any of the following flows: Cleaning and technical review aimed at reselling the product (working area 1), non-destructive disassembly with the objective of component recovery (working area 2) or destructive disassembly and material classification (working area 3) in order to subsequently hand in materials to specialized recyclers (Fig.3).

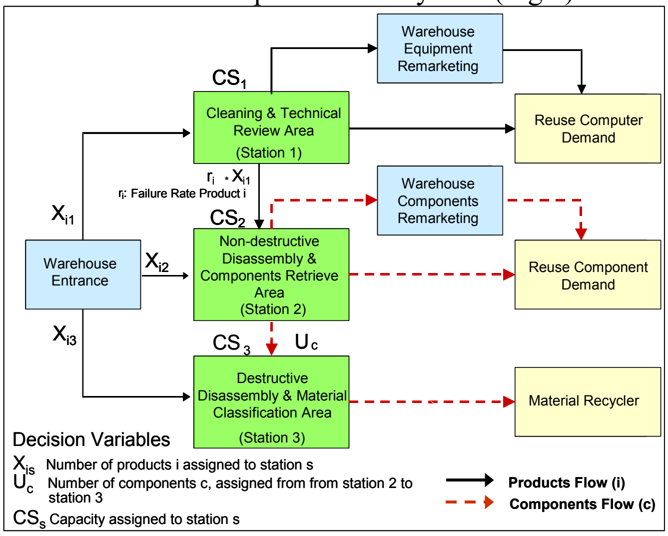


Fig.3 Model Recovery Center

Cleaning and technical review classifies products within three main groups according to optical appearance and condition. Products that both meet all technical review test criteria and resemble the visual appearance of new equipment are assigned to the first group. To the second group belongs equipment with reparable defects during the technical test e.g. defect CD disk drive or missing hard disk or optically have some deterioration e.g. housing scratch. The third group consists of products with irreparable defects e.g. defective mother boards or internal electricity supply. This products are sent to disassembly (station 2) in order to retrieve so many components as possible.

During non-destructive disassembly, reusable and remarket able components are retrieved, e.g. CD-player, floppy disk, graphic card. Components are sold as spare parts internally for recondition of equipment and externally to IT-reparation centers and second hand shops. All other components that have no resell potential are sent to station 3 to be classified according to their material. Therefore, there is a component flow between station 2 and 3.

Destructive disassembly and material classification, dismantles equipment in order to separate fractions according to materials e.g. aluminum sheets with different material purity, printed circuit boards (PCBs), plastic, precious metals, condensers and batteries. Some materials are sold to specialized recyclers, generating a revenue; others, generate extra costs as the company is entitled to pay for suitable disposal.

The uncertainty in equipment condition of recovered parts prior to inspection makes a consideration of failure rates necessary. The failure rate is the probability that equipment or components can be broken (unused) and unsuitable for refurbishing. The value can be obtained from historical data of the recovery center.

3.2 Linear Programming Model

The objective of the LP-Model is the cost optimal assignment of products to recovery and disassembly processes in order to maximize profit. Profit is calculated as the revenue of selling reusable products, components and materials minus process, storage and acquisition costs.

Model's index are i for equipment, c for component and s for working station. The objective function, given in equation (1) maximizes the difference between the revenue for selling refurbished equipment (SE_i), components (SC_c) and components to material recycling (SM_c) minus processing costs (PC), storage costs (WI, WE and WC) and acquisition costs (AC_i). Additionally, the objective function includes a penalization cost (α for equipment and β for components). Once finished products or components are available in the recovery center or warehouse entrance, the model strives to cover customer demand by considering a penalization cost for unfulfilled demand. Equipment and building components are related by a boolean variable (a_{ci}), with a value of 1 if component c is in equipment i and 0 otherwise. The LP-Model parameters are presented in Table 1.

Abb.	Meaning
α	*Penalization cost (€/unit) no-satisfied equipment demand*
β	*Penalization cost (€/unit) no-satisfied component demand*
a_{ci}	*Boolean variable: if the component c is in equipment i is equal to 1 otherwise equal to 0*
AC_i	*Acquisition cost of equipment i (€/unit)*
CR_c	*Number of components c on stock at warehouse component remarketing*
DC_c	*Demand of reusable component c*
DE_i	*Demand of reusable equipment i*
ER_i	*Number of equipments i on stock at warehouse remarketing*
NE_i	*Number of equipments i on stock at warehouse entrance*
PC	*Processing cost (€/minute)*
PT_i^1	*Processing time (minutes/unit) of an equipment i in station 1*
PT_c^2	*Processing time (minutes/unit) of a component c in station 2*
PT_c^3	*Processing time (minutes/unit) of a component c in station 3*
q_c	*Failure rate component c*
QC_c	*Maximum number of components c in the warehouse remarketing*
QE_i	*Maximum number of equipments i in the warehouse remarketing*
QW	*Maximum capacity (number of units) in the warehouse entrance*
r_i	*Failure rate equipment i*
SC_c	*Selling price (€/unit) reused component c*
SE_i	*Selling price (€/unit) reused equipment i*
SM_c	*Selling price (€/unit) for recycling component c*
TP	*Total available processing capacity (minutes)*
WC	*Storage cost (€/unit) per component in the warehouse for remarketing*
WE	*Storage cost (€/unit) per equipment in the warehouse for remarketing*
WI	*Storage cost (€/unit) per equipment in the warehouse entrance*

Table 1. Parameter LP-Model

The model's constraints assure all necessary conditions in the network. Equations (2), (3), (4) and (5) describe process capacity constraints. In a recovery center, there is a total available processing capacity (TP) e.g. man-hours that are assigned to each station; However, capacity assigned to station s (CS_s) is a decision variable (Table 2).

$$\sum_{i=1}^{m}\left(PT_i^1 \times X_{i1}\right) \le CS_1 \tag{2}$$

$$\sum_{c=1}^{n}\left[PT_c^2 \times \left[\sum_{i=1}^{m}\left(a_{ci} \times \left(r_i \times X_{i1} + X_{i2}\right)\right)\right]\right] \le CS_2 \tag{3}$$

$$\sum_{c=1}^{n}\left[PT_c^3 \times \left(\sum_{i=1}^{m}\left(a_{ci} \times X_{i3}\right) + U_c\right)\right] \le CS_3 \tag{4}$$

$$CS_1 + CS_2 + CS_3 = TP \tag{5}$$

Abb.	Meaning
X_{is}	*Number of equipments i to be send to station s*
U_c	*Number of components c to be send from station 2 to station 3*
CS_s	*Capacity assigned to station s (minutes)*
T_i	*Number of equipments i missing to satisfy the demand (artificial variable for penalization, with negative value or 0)*
V_c	*Number of components c missing to satisfy the demand (artificial variable for penalization, with negative value or 0)*

Table 2. Decision Variables LP-Model

$$MAX\left(\begin{array}{l}
\sum_{i=1}^{m}\left[-WE \times \left(\left(1-r_i\right) \times X_{i1} + ER_i\right) + \left(SE_i + \alpha + WE\right) \times T_i + \left(SE_i + WE\right) \times DE_i\right] - \sum_{i=1}^{m}\left(PC \times PT_i^1 \times X_{i1}\right) \\
+ \sum_{c=1}^{n}\left[\left(-WC \times \left(\left(1-q_c\right) \times \sum_{i=1}^{m}\left(a_{ci} \times \left(r_i \times X_{i1} + X_{i2}\right)\right) - U_c + CR_c\right)\right) + \left(SC_c + \beta + WC\right) \times V_c + \left(SC_c + WC\right) \times DC_c\right] \\
- \sum_{c=1}^{n}\left(PC \times PT_c^2 \times \sum_{i=1}^{m}\left(a_{ci} \times \left(r_i \times X_{i1} + X_{i2}\right)\right)\right) \\
+ \sum_{c=1}^{n}\left[\sum_{i=1}^{m}\left(a_{ci} \times X_{i3}\right) + U_c\right] \times SM_c - \sum_{c=1}^{n}\left[PC \times PT_c^3 \times \left(\sum_{i=1}^{m}\left(a_{ci} \times X_{i3}\right) + U_c\right)\right] \\
- \sum_{i=1}^{m}\left(AC_i \times NE_i\right) - \sum_{i=1}^{m}\left(NE_i - \sum_{s=1}^{3} X_{is}\right) \times WI
\end{array}\right) \tag{1}$$

The second group of constraints, equations 6, 7 and 8; control the storage capacity of warehouses entrance (QW), equipment remarketing (QE_i) and components remarketing (QC_c).

$$\sum_{i=1}^{m}\left(NE_i - \sum_{s=1}^{3} X_{is}\right) \le QW \tag{6}$$

$$(1-r_i)\times X_{i1} - DE_i + ER_i \le QE_i \tag{7}$$

$\forall i$

$$(1-q_c)\times\sum_{i=1}^{m}\left(a_{ci}\times\left(r_i\times X_{i1}+X_{i2}\right)\right)-U_c+CR_c-DCc\le QC_c \tag{8}$$

$\forall c$

Equations 9 to 13 are material flow constraints in the model in order to control product and component flows within the system.

$$X_{is} \ge 0 \tag{9}$$

$\forall i, \forall s$

$$U_c \ge 0 \tag{10}$$

$\forall c$

$$\sum_{s=1}^{3} X_{is} \le NE_i \tag{11}$$

$\forall i$

$$U_c \le \sum_{i=1}^{m}\left(a_{ci}\times\left(r_i\times X_{i1}+X_{i2}\right)\right) \tag{12}$$

$\forall c$

$$U_c \ge q_c \times \sum_{i=1}^{m}\left(a_{ci}\times\left(r_i\times X_{i1}+X_{i2}\right)\right) \tag{13}$$

$\forall c$

The last set of equations (14 to 18) defines the variables domain. The decision variables of the model are presented in table 2.

$$T_i \le 0 \tag{14}$$

$\forall i$

$$V_c \le 0 \tag{15}$$

$\forall c$

$$CS_s \ge 0 \tag{16}$$

$\forall s$

$$T_i \le (1-r_i)\times X_{i1} + ER_i - DE_i \tag{17}$$

$\forall i$

$$V_c \le \left[\sum_{i=1}^{m}\left(a_{ci}\times\left(r_i\times X_{i1}+X_{i2}\right)\right)\right] - U_c + CR_c - DC_c \tag{18}$$

$\forall c$

The penalization cost is a condition for making the model demand oriented. However, this is not a real cost for the recovery center. Therefore, real profit is the result of the objective function plus the penalization cost.

The LP-Model was implemented using the software AIMMS™. Required data regarding the recovery process was provided by a recovery center located in Germany. Using a page manager in the program AIMMS™, results of the LP-Model are graphically expressed. For example, in Fig.4 the profit contribution of each working station can be observed after solving the LP-Model. The profit contribution of station 3 (destructive disassembly and material classification area) is very small in comparison to the contribution of station 1 and 2, therefore it can not be identified in the graphic.

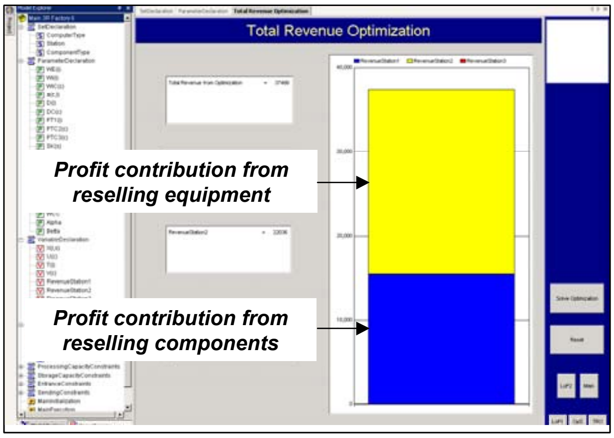


Figure 4. Example of Solving LP-Model Using the Program AIMMS™

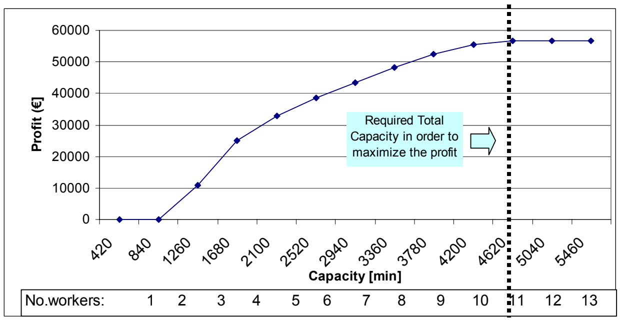
3.3 Solving the LP-Model under Specific Parameter

Relevant parameters such as supply, capacity and demand are selected in order to analyze how their variation influences the profit or objective function. Three scenarios are considered (Table 3).

Scenario	Supply	Capacity	Demand
1	fix	variable	fix
2	fix	fix	variable
3	variable	fix	fix

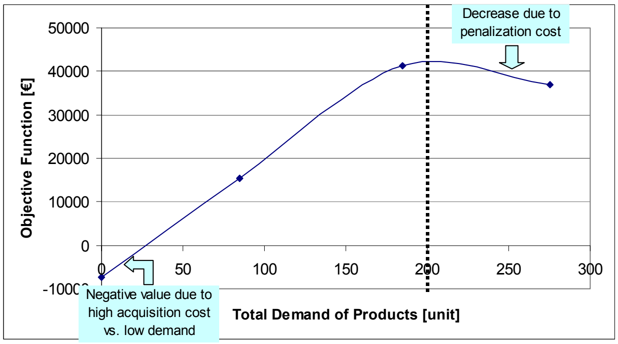
Table 3. Selected Scenarios

The first scenario describes the situation of finding out the required capacity at a recovery center in order to maximize profit under given supply and demand conditions (Graphic 1). If capacity is too small, the LP-Model becomes infeasible. Optimal total capacity is the threshold value which makes profit independent from capacity (as capacity increases, profit remains the same).



Graphic 1. First Scenario – Variable Total Capacity

The second scenario considers the variation of the objective function with product demand (Graphic 2). If demand is smaller than supply, the objective function value is negative due to acquisition costs and low material recycling revenue. The critical value of the demand is the point in which the objective function starts to decrease due to the penalization cost for unfulfilled demand.

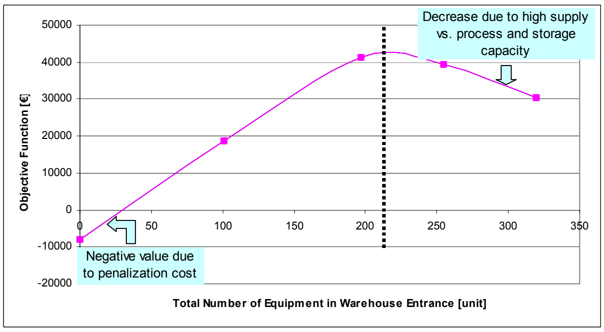


Graphic 2. Second Scenario – Variable Demand

The third scenario analyzes the variation of the objective function value with changing supply levels (Graphic 3). The critical supply level is the point in which the objective function gradient decreases because supply is too high in comparison to process and storage capacity. In this case, the model strives to send products to stations 2 and 3 in order to release space in the warehouse entrance at the expense of demand fulfillment.

3.4 Simulation

The simulation model was developed using the object oriented discrete simulator eM-Plant™. In the simulation, the material flow of three equipment types and eight components is modeled. Supply and demand are random data and inputted from the LP-Model.



Graphic 3. Third scenario – Variable Supply

Results of the LP-Model are taken as input values for the simulation, defining the number of products assigned to each working station as well as capacities. The simulation includes additional stochastic factors such as uniform distribution for products' and components' failure rates and normal distribution for processing times. Work stations are simulated by both single process stations and work places with the objective of measuring their efficiencies separately. Statistics of the simulation model e.g. output of the system and efficiency of working stations; are used to measure the performance of recovery center's operations.

4 Conclusions and Outlook

An LP-Model was developed to plan the operations in a recovery center. The LP-Model assigns the optimal number of products to each working area: recovery, disassembly to components retrieval and disassembly to material classification. The objective is to maximize profits from resold products, components and materials in comparison to the cost associated with product acquisition, recondition, disassembly and storage. The model also assigns the best distribution of the total available capacity to each working area. The LP-Model is solved in the program AIMMS™ and the results are implemented in a recovery center model simulated in eM-Plant™. In the future, the LP-Model shall be extended to consider different time periods. Strategies shall be also developed in order to control and react to unpredictable events such as changes in the market e.g. supply and demand variations and internal capacity changes.

5 Acknowledgments

We extend our sincere thanks to the graduate college "Stochastic Modeling and Quantitative Analysis of Complex Systems in Engineering" sponsored by the German Research Foundation (DFG)

References:

[1] Gartner Research, Rethink Initiative, http://pages.ebay.com/rethink/whatsewaste.html, 03-14-2005.

[2] European Parliament and Council, 2003, Directive 2002/96/EC on Waste Electrical and Electronic Equipment. In: Official Journal of the European Union, pp.24-37.

[3] Ricoh Company Ltda, 03-13-2005 http://www.ricoh.com/environment/management.html

[4] Vanegas M.; Kernbaum S.; Seliger G., Development of a control system for recycling networks considering uncertainty and variability. In: Proceedings global conference on sustainable product development and life cycle engineering, uni-edition, Berlin, Germany, pp. 175-178.

[5] Fujitsu Siemens Computer GmbH, Environmental Report 2003, http://www.fujitsu-siemens.com/recycling, 03-14-2005.

[6] Product Recycling HP http://www.hp.com/recycle, Global Citizenship Report 2003, http://www.hp.com/hpinfo/globalcitizenship/gcreport/products/recycling.html, 03-14-2005.

[7] Dell Recycling Service - Germany, http://www1.euro.dell.com/content/topics/topic.aspx/emea/topics/services/assetrecoveryservices?c=de&l=de&s=bsd (in German), 03-14-2005.

[8] Flection, Leading of Reuse in Information Technology, www.flection.com, 03-13-2005.