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Design of Reverse Logistics Networks for Multi-products, Multi-states, and Multi-processing Alternatives

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Abstract: This paper proposes a modeling methodology for designing reverse logistics networks. The model aims at determining location and missions of sites as regards recovery of unused products from ultimate consumers, valorization or clean disposal of recovered products, redistribution of reusable materials and attribution of new or reusable (valorized) products. Valorization activities refer to repair, refurbishing, reassembling, product disassembly for reusable material recovery (cannibalization) and recycling. Proportion of recovered product volumes to orient to valorization and clean disposal activities is not known a priori, but is determined according to demand and return volumes, site capacities and the general anticipated state of recovered product volumes. This model may be used to evaluate the impact of reintegrating valorized products (finished products and spare parts) into current supply chains initially designed for distribution and maintenance of new products only. The paper discusses key parameters such as the localization and estimation of potential returns and demands for new and reusable (valorized) products, as well as the probability that a returned product be in a specific state, which could lead to one or many processing alternatives (repair, disassembly, clean disposal, etc.). This mathematical model is inspired by the recent healthcare allocation and valorization of the wheelchair policy of the Province of Quebec (Canada), governed and managed by a governmental agency.

1.1 Introduction

Economic and environmental pressures to reduce consumption of non-renewable resources increase organizational responsibility regarding return or end of life products. The Kyoto Protocol, recent directives on electronic waste in Europe and significant return volumes in the electronic industry are some examples. Direct reuse, valorization activities, which refer to repair, refurbishing, reassembling, product disassembly for reusable materials recovery and recycling (Thierry *et al.*, 1995), and even clean disposal are being considered with increasing interest. For healthcare systems, product reuse is seen as an economical alternative in order to reduce continuously rising costs and to fulfill increasing demand while insuring high service level. A recent study concerning wheelchairs conducted by the *Régie de l'assurance maladie du Québec* (RAMQ) shows that valorization activities, realized autonomously by mandated rehabilitation centers, can improve accessibility to such devices while reducing expenditures (Côté *et al.*, 2003). Thus, the RAMQ and rehabilitation centers in the Province of Québec (Canada) are now interested in reviewing the actual configuration of their logistics network, which is initially designed only for allocation and maintenance of new products. The RAMQ is also involved in the impact evaluation of such a configuration on logistics costs and service level. New modeling approaches of logistics networks design must be investigated in order to consider the recovery of unused products from ultimate consumers and the use of valorized products (finished products and spare parts) instead of new. Generalized approach is proposed in this paper.

Strategic decisions concerning reverse logistics network design concern recovery, processing and redistribution. Sites have to be located. All logistics activities need to be assigned to suitable sites, while respecting capacity and ensuring effective and efficient response to requests expressed to networks. Different costs and service levels will be met according to choices made.

Product orientation to processing alternatives can influence the network configuration with business units being dedicated to specific processing alternatives and even to one or several products. Products can be used to meet network needs in a variety of ways: they can be repaired, refurbished or reassembled for finished product supply, or disassembled for spare parts supply. If preferable, products can even be recycled or simply cleanly disposed. Product state, demand and return expressed to the network and site capacities all determine how product volume will be processed and whether processed products will be used to respond partly or completely to network needs. *The objective of this article is to suggest a methodology for designing the logistics network while evaluating the strategic proportion of product to direct towards each of these alternatives in an efficient and effective way to meet network needs*.

This paper presents various models suggested for specific reverse logistics networks design. In light of these models, a logistics network reengineering process is suggested to represent networks flows in a multi-products, multi-states and multi-processing alternatives context. It deals with the design of reverse networks, while considering current supply chain networks, to efficiently supply processed products as alternatives to new. To complete it and to widen horizons, new parameter definition approaches and a mathematical model are proposed.

1.2 Related reverse logistics design models

Several models for reverse logistics networks design are proposed in the literature (Table 1.1). The formulation of these models proposes some distinctive modeling methods in addition to those traditionally developed for supply chains (Jayaraman and Pirkul, 2001; Martel, 2001; Flapper *et al.*, 1995; Geoffrion and Graves, 1974).

1.2.1 Localization and determination of demand and return volumes

One significant distinction with respect to modeling of reverse logistics networks is underlined by Fleischmann (2001). Within the supply chain context, models are generally developed in such a way that networks satisfy final demand from consumers (pull flows); while flows must be directed, as best as possible, in reverse logistics networks (push flows). In some cases, processed products can be reintroduced into the supply chain to partially or completely satisfy demand, thus causing disequilibrium between supply and demand. Most of the recent models take this situation into account with demand, recovery and site capacity constraints. Closed or open supply loop, with products reintegration in the original supply chain or in alternative markets, is then considered.

Some proposed models consider that unused products from ultimate consumers are already in established recovery centers whereas others use the concept of user zones. For each of these zones, a demand and a return volume is generally defined upfront (Listes, 2005; Lu and Bostel, 2005; Fleischmann, 2001) or return volume is represented as a fraction of the demand volume (Fandel and Stammen, 2003). They are used to locate recovery centers, processing centers and warehouses and to evaluate transportation costs, while allowing consideration of service level. Indeed, zones can be defined according to distance separating user zones from sites offering products and services (service centers).

1.2.2 Product families and bill of materials

Few models deal with a multi-commodity networks. Some tackle it for product decomposition. It is notably approached by Fandel and Stammen (2003) with reverse bill of materials or by Spengler *et al.* (1997) and Shi (2001) with mass relation between materials. The former approach specifies which product families can be recovered from others and which disassembly sequence is to be used.

1.2.3 Processing conditions and product states

Generally, only one (Listes and Dekker, 2005; Fandel and Stammen, 2003; Jayaraman *et al.*, 2003; Shih, 2001; Krikke, 1998) and sometimes two options for processing alternatives (Listes, 2005; Lu and Bostel, 2005; Fleischmann, 2001) are considered in proposed models. When more than one processing alternative is considered, the proportion of products directed towards one or another alternative is generally determined and fixed *a priori*. Fleischmann (2001) proposes a lower bound on material quantity to be eliminated and thus considers technical or economical infeasibilities related to product reintroduction into market. A certain degree of freedom is then considered as to processing alternatives.

According to the state of recovered product volumes, different processing alternatives may occur. Listes and Dekker (2005) consider this aspect by assigning states with proportions of recovered products. A processing alternative is associated to each state, and processed products are used to fulfill a given demand.

Typically, recovered products are reintroduced in networks in a state similar to those in the supply chain. Hence, new or like-new product reuse or sales of only valorized products represents distribution activities in those networks. In this way, customers do not have a valorized products alternative to new or as new products. Valorized products, especially in a public setting, may represent an economical supply source and a compromise solution allowing improved performance in terms of service delay and satisfaction. It may also have an impact on logistics network environmental performance. Little work evaluating these impacts has been done.

Several methods have been proposed to establish recovery and processing strategies and to evaluate their impact on costs and benefits to an organization (Teunter, 2005). Some contributions at the strategic level, such as Krikke (1998), aim at defining the proportion of product to be directed to each processing alternative *a priori*, according to the quality of returned product and their constitutive parts, and then to configure the network in consequence. Teunter (2005) has adapted this preliminary approach by considering multiple disassembly processes and partial disassembly in addition to product quality.

Some reverse logistics specificities are mentioned in the literature; however, these references offer few suggestions on how to explicitly integrate them in the modeling stage of logistics networks. When specificities are introduced into models, parameters are generally defined as deterministic and little flexibility is suggested regarding recovery, processing and redistribution. Most of the models proposed in the literature do not approach the fact that the same recovered product can be used to meet various needs, in particular in terms of valorized finished products and spare parts. Different processing alternatives may also arise according to product condition and the capacity and needs in a network. Ideally, more than one processing alternative should be considered to improve value recovery possibilities and to limit environmental impacts. However, product flow orientation is complicated in such a context. Additional efforts are then required to define products, customers and organization activities, and thus, to detail all potential networks flows in a simple way. This paper aims to contribute to the development of an extended model tackling these issues. Characteristics of this model, compared to those identified in the literature, are summarized in Table 1.1.

Table 1.1. Main characteristics of related reverse logistics design models

MODEL CHARACTERISTICS		[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]
	Covered logistics functions											
	Product development					✓		✓				
	Procurement of material					✓		✓				✓
	Transformation of material to intermediate and finished product			✓		✓		✓	✓		✓	

	Distribution of finished product to consumers			✓		✓		✓	✓		✓	✓
	After sales service (such as maintenance)											✓
	Recovery of unused products	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Transformation of recovered products to raw material, intermediate and finished product	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Redistribution of reusable materials to consumers		✓	✓	✓			✓	✓	✓	✓	✓
Localization and determination of demand and return volumes	Reverse logistics integration to current supply chain											
	Reverse logistics only	✓			✓		✓					
	Closed and open supply loop		✓	✓		✓		✓	✓	✓	✓	✓
	Service features											
	Consumer requests satisfaction (demand and/or recovery)	✓[a]	✓	✓	✓	✓	✓[a]	✓	✓	✓	✓	✓
	Maximum time (distance) to serve consumer (with the use of user zones)			✓		✓		✓	✓		✓	✓
	Demand and return volume											
	Dependent					✓						✓
	Independent	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
Product families and bill of materials	Multi-commodity model	✓			✓	✓		✓				✓
	Bill of materials (BOM)											
	Assembly					✓		✓				✓[b]
	Disassembly (1. quantity of raw materials, components or assembly modules to recover from a product; 2. mass relation between materials)	✓ 2			✓ 2	✓ 1		✓ 1,2				✓ 1
	Technical, environmental or others ass./dis. feasibilities					✓						✓
Processing conditions and product states	Multi-state model									✓		✓
	Multi-processing alternative model											
	Direct reuse (product quality as rigorous as those distributed in the current supply chain)		✓	✓		✓		✓	✓	✓	✓	
	Valorization activities (repair, refurbishing, reassembly, cannibalization, recycling) (product quality less rigorous than new)	✓[c]	✓				✓	✓		✓		✓
	Clean disposal (end of life of products)	✓	✓	✓			✓	✓	✓	✓	✓	✓
	Product flow orientation											
	Fixed recovered product volume (1. known volumes; 2. portion of sales)	✓ 1	✓ 1	✓ 1	✓ 1	✓ 2	✓ 1	✓ 1	✓ 1	✓ 1	✓ 1	✓ 1
	Fixed proportion of recovered product volume oriented to each processing alternatives	✓	✓		✓	✓	✓		✓	✓		
	Lower bound on product volume to be cleanly disposed (1. after sorting and grading; 2. after processing)			✓ 1					✓ 1		✓ 1,2	✓

Upper bound on product volume to be repaired, refurbished or reassembled (reintroduced in a network in their original form)							✓				✓
Reusable products reintegration (according to 1. demand; 2. sites capacities; 3. product volume state)	✓[d]	✓ 1	✓ 1	✓ 2	✓ 1,2	✓ 2	✓ 1	✓ 1,2	✓ 1,2,3	✓ 1	✓ 1,2,3
Dynamics characteristics (multi-period)					✓						
Stochastic features											
Demands of products and components								✓	✓		✓ *
Portion of demand fulfill with valorized products											✓ *
Recovery of unused products								✓	✓		✓ *
Portion of product to orient to each processing alternative											✓ *
Kind of model											
Allocation	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Localization	✓[e]	✓	✓	✓	✓	✓	✓[e]	✓	✓	✓	✓
Modeling of network flows											
Chains			✓			✓	✓			✓	
Arcs	✓	✓		✓	✓			✓	✓		✓
Objective function											
Minimization of costs	✓	✓	✓			✓	✓[f]			✓	✓
Maximization of profits				✓	✓			✓	✓		
Cost included											
Fixed facility costs	✓[g]	✓	✓	✓	✓	✓	✓[g]	✓	✓	✓	✓
Development costs					✓						
Production costs			✓		✓		✓	✓	✓	✓	
Handling and transportation costs	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Carrying costs		✓	✓	✓	✓				✓		✓
Penalty costs for not serving demand			✓								
Penalty costs for not collecting from user			✓					✓			
Processing costs	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Value recovery from using valorized products											
Decrease of production load or supply for new products			✓				✓	✓		✓	
Revenue from selling valorized materials				✓	✓				✓		
Use of valorized products at lower cost instead of new											✓
Capacity											
Development					✓						
Transportation											✓
Processing	✓	✓		✓	✓	✓			✓		✓
Production					✓						

Storage				✓	✓	✓			✓		✓
Supply					✓						
Bound on number of facilities	✓[h]			✓	✓	✓					
International features					✓						
Stochastic formulation											
Two stage model – analysis of a fixed scenario set								✓			
Two stage model – analysis of finite but large scenario set defined with sample average approximation (SAA)											✓ *
Three stage model – analysis of a fixed scenario set									✓		
Method of solution applied					N/A						
A heuristic method						✓		✓		✓	
Commercial MIP solver	✓	✓	✓	✓			✓		✓		✓ *

[1] Spengler *et al.*, 1997; [2] Krikke, 1998; [3] Fleischmann, 2001; [4] Shih, 2001; [5] Fandel and Stammen, 2003; [6] Jayaraman *et al*., 2003; [7] Bloemhof-Ruuward *et al.*, 2004; [8] Listes, 2005; [9] Listes and Dekker, 2005; [10] Lu and Bostel, 2005; [11] Chouinard *et al.*, 2006.

a Recovery only
b Reassembly considered by the replacement of unusable components or assembly module (component or assembly module in state s=3 and s=4)
c Multi recycling processes
d Reusable products reintegration according to process capacities
e Processes localization
f Minimize economic costs, energy use and residual waste
g Fixed cost of selecting a process
h Bound on number of realizations of a process at a location
* Work in progress

1.3 Logistics network reengineering process

First, the necessary information to dress a total portrait of the organization, as regards its products, ultimate consumers, capacities, constraints, etc., is identified. Such a parameter definition step is critical in the design methodology. In his book, Shapiro (2001) has extensively discussed the importance of parameter definition in supply chain design. Additional aspects are to be considered with a view to their adaptability to reverse logistics integration. Considered parameters include here: i) demand and recovery zones (user zones) and demand and return volumes for each zone (service forecasts); ii) product families; iii) bill of materials, including recovery; iv) processing conditions and product states; (sections 1.3.2-1.3.5).

The next step of this reengineering process approached here is the development of a mathematical model. It shows how reverse logistics characteristics can be conceptualized and integrated (section 1.3.6 and Appendix) with the use of these parameters. Additional required flow conservation constraints are detailed with figures in the paper. Constraints of the mathematical model, detailed in Appendix, are presented with notations using square brackets in these figures ([Eq.]).

1.3.1. Studied context

The network (Figure 1.1) consists of service centers already in place satisfying ultimate consumers within user zones defined geographically. These centers offer new and valorized products as well as maintenance and recovery services. New products are delivered by established external suppliers. Each service center can also play the role of recovery center, using their private vehicle fleet or a service logistics provider. Voluntary returns from ultimate consumers are possible, following product replacement or maintenance activities, and recovered products must then be forwarded to a suitable processing center, for finished product repair, components disassembling and refurbishing, or recycling and clean disposal. Product orientation to processing alternatives depends on product state, site capacities and demand for valorized products (finished products and spare parts). Valorized products generated in these centers are stored to adequately meet future service and processing centers needs, to repair products. Both new and valorized spare parts can be used for product repair. Recovery and processing centers and warehouses are to be located to improve accessibility to valorized materials, and to minimize costs of integrating such reverse logistics network with the current supply chain. Use of valorized products is cheaper than new. The network reported here is a generalization from the wheelchair allocation problem in Quebec, (Chouinard *et al.*, 2005; Chouinard, 2003).

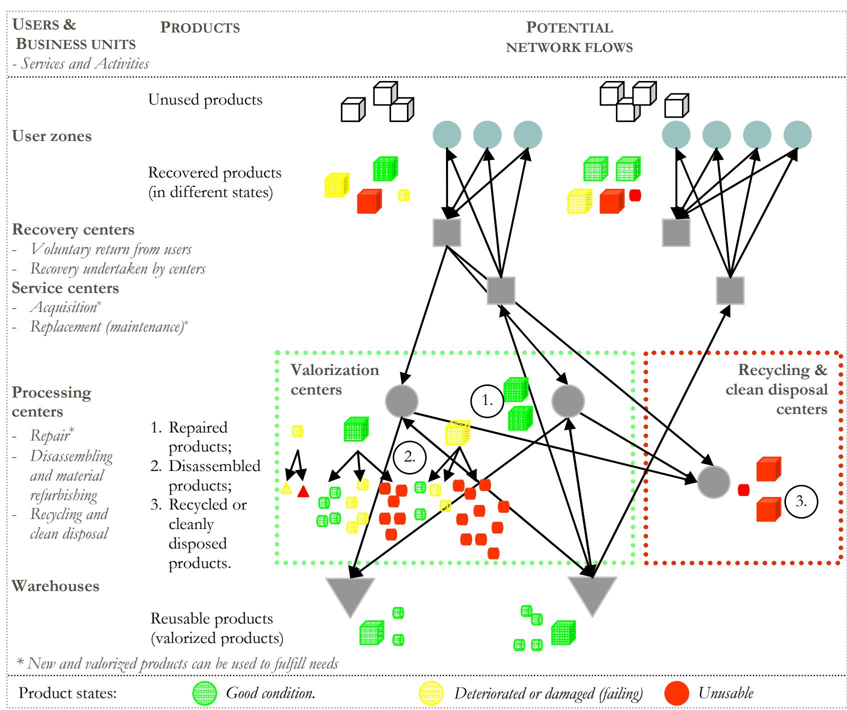


Figure 1.1. Reverse networks business units, products and potential flows

1.3.2 Localization and determination of demand and return volumes

The number of ultimate consumers (users) is too high for each to be considered individually at the design stage of the logistics network. They are represented by restricted geographical, here called user zones, which allow localizing and forecasting demand and return volumes. Zones can also be assigned to proper service and recovery centers according to distance separating them. It is useful to estimate transportation costs, particularly when more than one transportation mode may be considered to fulfill demand or to recover products.

For supply chains, user zones are defined as demand zones. A general approach to locate these zones is to weight customer coordinates (X_i, Y_i) with their demand volume (W_i), known and fixed *a priori*, as follows:

$$X_j = \sum_{i \in V_j} W_i X_i \Big/ \sum_{i \in V_j} W_i \quad j = 1, \ldots, m\,; \qquad Y_j = \sum_{i \in V_j} W_i Y_i \Big/ \sum_{i \in V_j} W_i \quad j = 1, \ldots, m$$

where V_j is zone j gathering some customers i.

Clustering methods are generally recommended for the aggregation process (Ballou, 1994). Some general rules are suggested in the literature to control location, size and number of zones for supply chains (Ballou, 1994).

It is difficult to apply this approach to reverse logistics as products in circulation represent potential returns, which can feedback the organization. In most reverse logistics cases, return origins and quantities are not known *a priori*.

In a context where reverse logistics are integrated into the supply chain, modeling of such user zones must consider two types of flow, direct (demand) and reverse flows (recovery). These two types of flows can be treated by distinct or common geographical zones (Figure 1.2). The choice will depend on the studied context and five principal factors can influence this choice:

- ***Localization of service centers and recovery centers in common and/or distinct sites:*** common sites can lead to common zones for both direct and reverse flows;
- ***Different territory covered by service centers and recovery centers:*** for common sites, as regards service centers and recovery centers, same territory cover can lead to common zones;
- ***Link between direct and reverse flows:*** dependent direct and reverse flows can lead to common zones;
- ***Service costs (delay, transportation costs) to evaluate only direct or reverse flows or for the two types of flows jointly:*** distinct zones can facilitate evaluation of service costs, particularly when evaluated differently for direct and reverse flows;
- ***Users or customers and products common to demand and recovery processes:*** different users and products as regards demand and recovery can require distinct zones.

In addition, various **service types** can arise in networks, both for demand and recovery. **Demand** can come from existing consumers, but also new consumers. It can occur during ***acquisition*** (*new product* or *material addition* to a product in circulation) or ***product replacement*** (*exchange* or *maintenance*). Demand can be satisfied by new or valorized products. **Recovery** can arise following ***voluntary return*** (*replacement* or *unused product*) on behalf of the user or from ***recovery undertaken by the organization*** (*private vehicle fleet* or *logistics service providers)*. Products in different states can be involved and require the use of distinct resources. Distinct geographical areas can be considered and particular sites can be used for each service type. Figure 1.2 presents different service types that can occur between user zones and sites (service and recovery centers).

According to the situation, product and ultimate consumer (user) characteristics can influence organization activities. Certain information known by the organization that links users and products, such as contract conditions, can also be used to evaluate needs expressed in the network. Relevant information can then be used to accurately forecast possible services in a dynamic and highly uncertain environment caused by reverse logistics integration to the supply chain:

- **User status:** Age, Gender, Localization, Condition and Intensity of use, Consumer behaviour, Social class, Etc.
- **Product status:** Product family, Bill of materials, End of guarantee, Value, Aesthetic and Technical quality when put on the market (e.g.: new or valorized) or in circulation, Age, Failure law (residual lifespan), Etc.
- **Organization:** Localization, Operation context of service and recovery centers, Condition at market entry (sale or renting), Contract conditions, Service type, Product state during activities, Etc.

The use of this information to create forecasts requires data and, consequently, ultimate consumers (users) and product families (section 1.3.3) in circulation needs to be localized beforehand. Therefore, it is preferable to initially locate users and product families in circulation in restricted geographical areas and then establish or distribute forecasts to these zones according to their composition. However, the adopted approach must consider potential errors related to zone definition:

- **Positioning errors** (Hillsman and Rhoda, 1978 in Ballou, 1994):
    - Total estimated service cost compared to real service cost met when all consumers (for each service type) of a zone are served individually;
    - Inappropriate allocation of consumers to sites and erroneous location of these sites due to an aggregated rather than individual demand.
- **Service forecast errors:**
    - Increased forecast errors due to poor consumers aggregation or poor service characterization.

The level of details relating to the extent of geographical areas, by individually approaching or not direct and reverse flows and by separately considering or not each service type, has an impact on the evaluation of network performance. In fact, different users and products can be involved according to the situation and will require products and services at different costs and service levels.

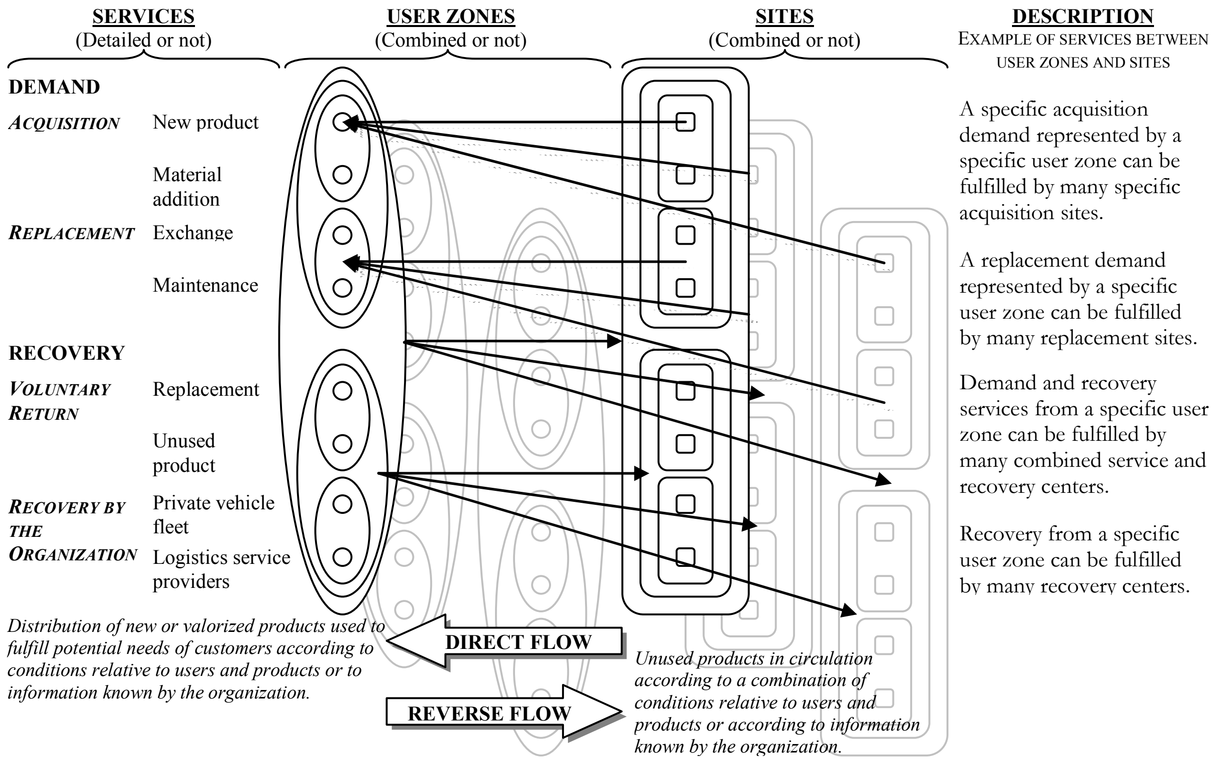


Figure 1.2. Possible scenarios of user zone modeling

1.3.3 Product families

Product variety managed by an organization can be relatively significant. To facilitate later stages of logistics network design, products (finished products, assembly modules and components) are generally gathered in families. A family contains products with similar characteristics and which use equivalent processes throughout the logistics network. Products are gathered, for logistics networks design, on the basis of logistics processes characteristics.

Definition of product families is usually done with ABC classification methods, Analytic Hierarchy Process (AHP) or clustering algorithms (Ramanathan, 2005; Srinivasan and Moon, 1999; Flores et al., 1992; Ernst and Cohen, 1990). For the supply chain, products are gathered according to the following process characteristics (Martel, 2004):

- Demand profile (risks, seasonality, ...);
- Production, storage and handling technologies used;
- Distribution channels and service levels required;
- Means of transportation considered.

However, to extend these approaches to reverse logistics, it is necessary to consider the fact that products can be reintroduced in the network at several levels and may be subject to modifications before reintegration. Additional characteristics then need to be considered (Chouinard, 2003; Krikke, 1998):

- Technical feasibility to recover and process products;
- Commercial feasibility to redistribute reusable products;
- Environmental feasibility to recover and process products;
- Material flow (demand and return volume, product volume state);
- Economical and environmental costs and benefits in products lifecycle.

Distinct families can be defined for supply chains and reverse logistics, however, considering both at once would complicate subsequent analysis steps of logistics network design. Some links may also occur between different products gathered in different families and product substitutability may be allowed in some network stages. The suggested methods can then require explicit use of bills of materials, but they must be adapted to a reverse logistics context.

1.3.4 Bill of materials

In a supply chain context, different volumes of material (raw material, component or assembly module) families can be assembled at different stages of the manufacturing system to fulfill demand for finished product families. Regarding reverse logistics, different volumes of material families can be disassembled from recovered finished product families, to recover those in good condition or to replace the defective ones. These activities can occur at different stages of the logistics network and may involve many sites. For logistics networks design, bill of materials (BOM) is used to specify material needs or supplies, and assembling or disassembly sequence at each stage of the network (.Figure 1.3).

Some papers suggest clustering and association mining methods to define BOM. Romanowski *et al.* (2005) propose a method that clusters design of products, represented as BOM, into product families. Srinivasan and Moon (1999) suggest an approach to define product families, which takes into account BOM and the fact that products may be used at different levels of the network.

Contrary to BOM considered for supply chains, which is presented by an acyclic oriented graphic, cycles can occur between graph nodes in the context of reverse logistics (Figure 1.3). This characteristic arises with material flows that can occur in both directions, to consider (re)assembling and disassembling. Moreover, nodes can be presented in two generic forms, such as new products or as recovered and valorized products. These later nodes represent, respectively, products that can be disassembled in material (raw material, component or assembly module) families in various states (section 1.3.5) and products that can be used as an alternative to new products, but of poorer quality. As for supply chain, quantity associated with each link of the BOM indicates the product volume portion, which can be involved in a particular network stage. Bold arrows in Figure 1.3 represent requirements of new products for assembling, while dotted arrows represent product requirements for reassembling or product supplies while disassembly. It is considered here that only new products can be used in new product composition, whereas new and valorized products can be used to valorize recovered product.

Quantity characterizing each link ensures flow conservation. For new product assembling, it is then possible to ensure new materials (raw material, component and assembly module) availability for production. For product reassembling, in particular during maintenance or valorization activities, the role is similar. However, contrary to new product assembling, reassembling can be done with either new or valorized materials, according to the given case. Flow conservation constraints intervene here to ensure that the volume for a given material, of new and valorized material necessary for product reassembling, does not exceed the specified quantity characterizing the link between the two involved nodes.

For recovered product disassembly, flow conservation constraints determine the probability to recover a volume of material (raw material, component or assembly module) family from a product family. An additional parameter must be considered in order to specify if it is possible to disassemble the targeted product family, as suggested by Fandel and Stammen (2003). This aspect takes technical, economical and other constraints (disassembly feasibility) into account that can occur while disassembly (Figure 1.3). In our studied context, recovered product families can generate only valorized materials, but in various states; therefore other constraints are necessary if this aspect is to be considered (sections 1.3.5 & 1.3.6.1-1.3.6.2).

1.3.5 Processing conditions and product states

Product families and bill of materials are defined for the supply chain by considering flow of material in identical state to produce finished products respecting quality standards of the organization. However, product families in different states can occur for reverse networks.

During the processing of recovered products, product state will determine if it can be directly reused or has to be oriented to some other processing alternative. Subfamilies then need to be defined and assigned to product families in the mathematical model, according to their state. These states depend on the average general condition of a product family in circulation within a zone (section 1.3.2). They also depend on the processing alternative retained for a specific disassembled product family of a given state, since some alternatives may be more destructive. These states can be fixed *a priori*, however it is probably more convenient to assign state to product families with probability distribution functions integrated to the model. This approach then considers uncertainties regarding processing and reuse of recovered product volumes.

Within the framework of this paper, four states can be assigned to products:

- New: s = 1;
- Used and dedicated to repair (valorized): s = 2;
- Used and dedicated to disassembly and spare parts refurbishing: s = 3;
- Used and dedicated to recycling or clean disposal: s = 4.

Probability distribution functions (Figure 1.4) may describe the quantity and state of all recovered materials in the network from ultimate consumers such as those generated following disassembly. These functions would be defined for each product family considered in the model (section 1.3.3). Material volumes produced while disassembly will have to respect the bill of materials (Figure 1.3).

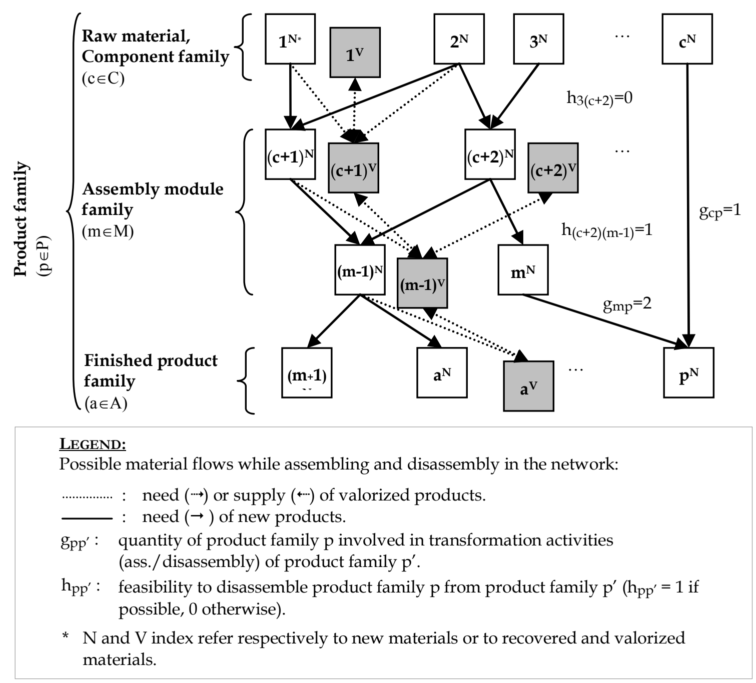
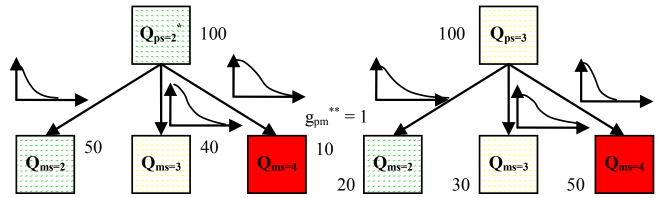


Figure 1.3. Partial bill of materials for modeling logistics networks

A given state will predestine product families to a certain processing alternative. However, the model suggested in this paper offers a certain degree of flexibility in this regard (section 1.3.6.2).



*Q_{ps} and Q_{ms}: Quantiy of product family p or assembly module family m in state s.
**g_{pm}: quantity of assembly module family m involved in transformation activities (ass./disassembly) of product family p.

Figure 1.4. Valorized material production function

1.3.6 Location-Allocation model

The developed mathematical model, introduced in this section, consists primarily in determining a reverse network configuration while considering the use of current supply chain sites and additional business units. It concerns the location of recovery and processing centers and warehouses. Material flows are summarized and represented in figures, which indicate the related model constraints. Details concerning model equations are given in Appendix.

The objective function of the model is to minimize:

- Fixed costs (recovery and processing centers and warehouses) + variable processing costs + material flow costs (handling, storage and transportation) between sites [Eq. 1.1].

Material flows are subjected to the following constraints:

- Demand [Eq. 1.2-1.6] (section 1.3.6.1);
- Recovery [Eq. 1.7-1.9] (section 1.3.6.1);
- Preliminary product flows orientation [Eq. 1.10-1.11] (section 1.3.6.1);
- Elaborated product flows orientation [Eq. 1.12-1.15] (section 1.3.6.2);
- Disassembly [Eq. 1.16-1.23] (section 1.3.6.2);
- Recycling or clean disposal [Eq. 1.24-1.27] (section 1.3.6.2);
- Material replacement [Eq. 1.28] (section 1.3.6.2);
- Valorized products supply and demand [Eq. 1.29-1.30] (section 1.3.6.2);
- Capacity (transportation, processing, storage) [Eq. 1.31-1.34].

Accent is placed on specific constraints related to product flows orientation according to network condition (supply and demand volumes, site capacities) and general product volumes state (Figure 1.5).

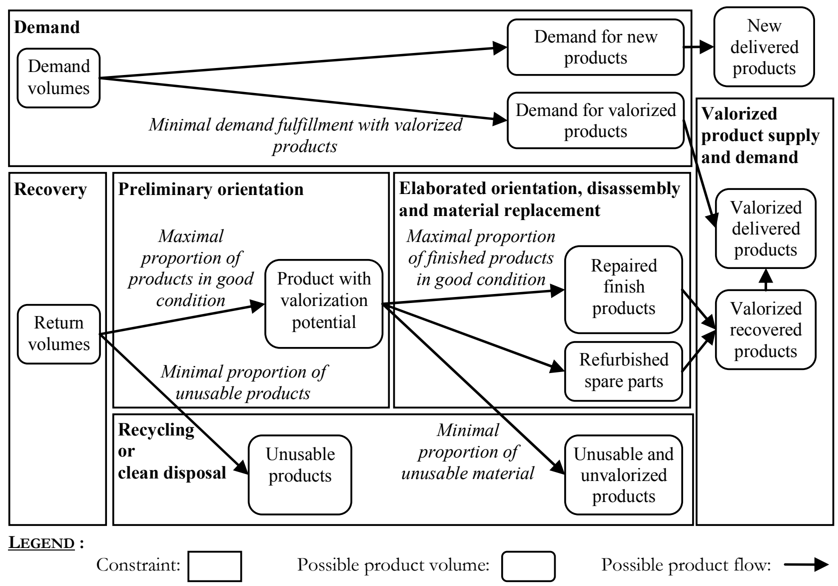


Fig 1.5. Summarized relation between material flows and model constraints

1.3.6.1 Potential logistics network

The potential network for the considered context (section 1.3.1) is presented in Figure 1.1 and is detailed in the text starting from user zones, where reverse flows are initiated.

Users and product families in circulation are aggregated in restricted geographical areas, indicated as **user zones** (section 1.3.2). ***Recovery centers*** are supposed to be located in a restricted number of ***service centers*** in this article. Location of recovery centers will be evaluated by scenarios analysis, for which user zones will consequently be assigned according to distance separating them.

Material recovery initiates reverse flows in the network. Aggregated flows of recovered product families are split between the different **processing centers,** which are either ***valorization centers*** or ***recycling and/or clean disposal centers***. The former provide effective product reintegration into the original logistics network (closed supply loop) and the latter handles end of product family lifecycle within this same network (open supply loop). Valorization centers can use internal logistics network units, such as service centers with necessary expertise and resources to deal with valorization activities or centers dedicated to these activities, or third parties. Recycling and clean disposal centers are third parties.

Valorized material volumes, which can extend product family lifecycle within the original network, are stored before their delivery to ultimate consumers, and both public and private **warehouses** are considered.

Warehouse and processing center location and capacity need to be determined to ensure a better delivery delay for valorized products in comparison with new products from suppliers, according to their distance from service centers. These

sites must be able to effectively meet network needs, at both service (acquisition and replacement, including maintenance) and processing centers (valorization activities, to repair recovered products).
Supply of new products comes from external **suppliers**, which deliver new finished products and spare parts on demand. Each supplier offers a specific product variety, represented by product families. Transportation costs are included in acquisition costs.

Transportation between various nodes within the network (excluding suppliers) is carried out by logistics service providers or private vehicle fleets from service centers. Transportation is not considered for product acquisition and in some return circumstances, specifically for replacement, since ultimate consumers have to visit service centers. Recovery services are offered by the organization to ensure a greater possibility of recovery, which can be particularly significant when external pressures are exerted on the organization (by governmental agencies or other).

1.3.6.1 General material flows orientation

In addition to demand and recovery volume within the potential logistics network sites and their capacities, material flows between each site are also split according to product family condition. Details of these flows are schematized in Figure 1.6. Material flows within logistics networks, for both direct and reverse flows, are initiated at the user zone level.

In this article, demand expressed by each user zone and, consequently, to the associated service center arises under two circumstances: acquisition and product replacement (including maintenance). For these two situations, customers or users have to visit service centers where demand can be filled by either new or valorized materials. However, a portion of needs must be filled by valorized materials, according to customer or user requirements and according to organization policies.

As with demand, two recovery situations can arise: voluntary returns and recovery steps undertaken by the organization. Different recovery costs are then generated, not only according to return type but also according to recovery resources needed (section 1.3.2), since a proportion of unused product cannot be recovered from ultimate consumers by the organization, particularly when they cannot be found. No penalty costs are considered for these products.

As previously indicated, four states can be assigned to product families (section 1.3.5), each state requiring different processing processes and resources. In order to avoid unnecessary material flows in the network at a strategic level, preliminary orientation (Figure 1.6) is carried out at the recovery center level (service centers). Volume of product families recovered is oriented in the network based on the general state of returned products (finished products or spare parts recovered during maintenance activities for example). This volume is then separated into two categories. All materials with reuse potential are directed towards valorization centers, whereas all materials in deteriorated condition are directed towards recycling or clean disposal centers.

1.3.6.2 Elaborated product flows orientation and processing

The general state of a product family volume can determine its direction towards a given processing alternative, but this alternative is not necessarily retained for the entire volume. In fact, according to network needs and site capacities (processing centers and warehouses), it is also possible that a portion of this volume is directed towards other alternatives (Figures 1.7). In this article, only used products (s=2, s=3 and s=4) are recovered by service centers. The volume of these products is then split between the processing centers.

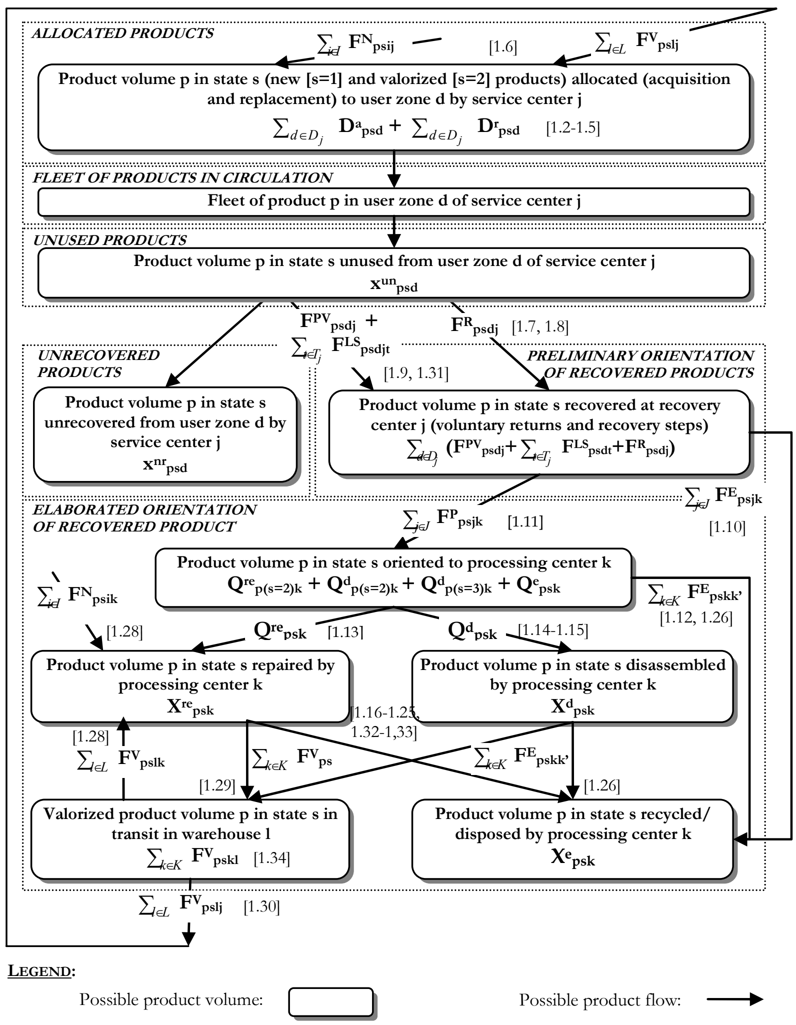


Figure 1.6. Principal annual aggregated material flows within the potential logistics network.

The state of a product family volume directs it to a given processing alternative. However, it can be reoriented towards a lower processing alternative, presenting a lower recovery value. In this article, three processing alternatives are distinguished, and given in descending recovery value. These alternatives are:

- **Repair** [s=2 – finished products only in this work]**;**
- **Disassembly and refurbishing** [s=2-3 – finished products and spare parts]**;**
- **Recycling or clean disposal** [s=2-4 – finished products and spare parts]**.**

A higher ranked processing alternative is initially considered; however, when circumstances do not allow this (demand, overflow of recovered products at the processing centers and warehouses), a portion of product family volume can then be directed towards the lower ranked alternative (Figure 1.7). The last possible processing alternative, for all recovered materials, is recycling or clean disposal. End of product family lifecycle is reached when these alternatives are taken. Only recycling can represent here a source of recovery value. This decision rule for processing applies to both finished product and spare part families.

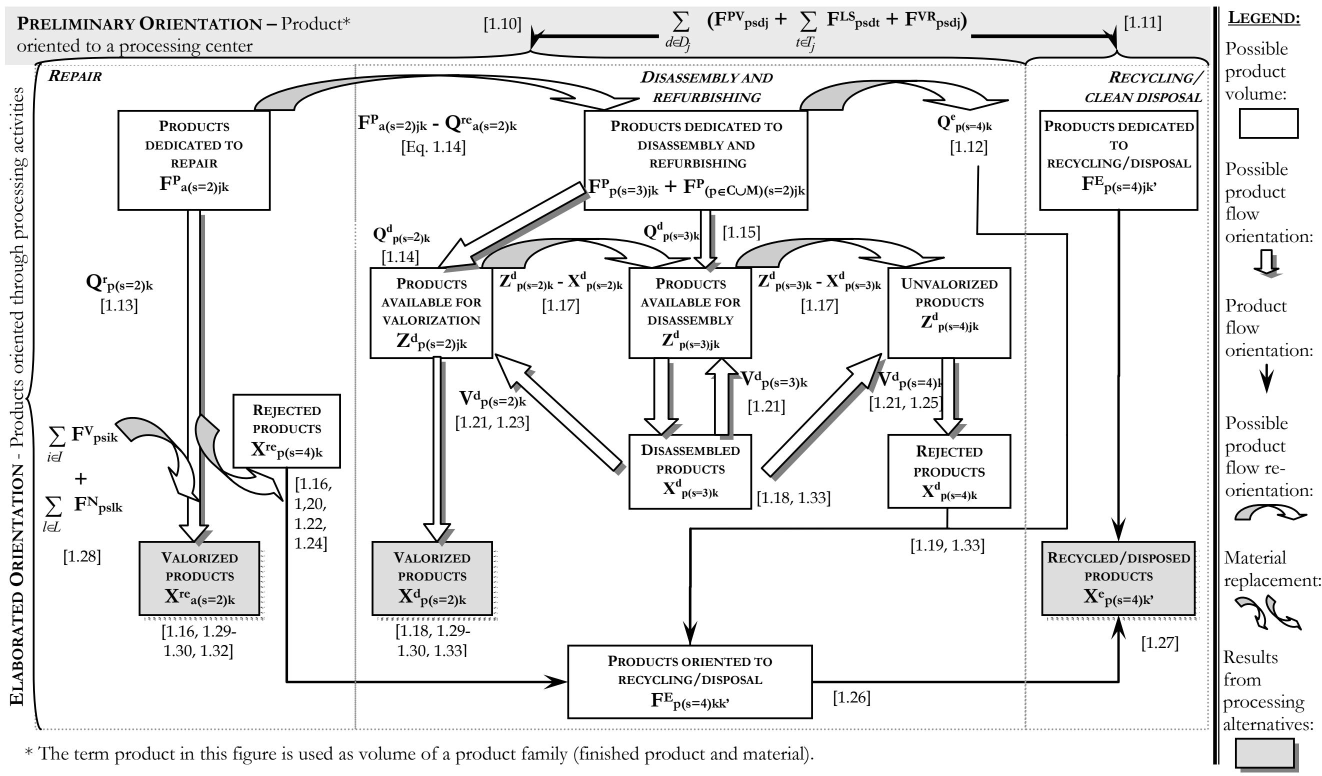
Volume of products directed towards valorization centers can be handled in two ways: it can be repaired (s=2) or disassembled for spare parts refurbishing (s=2 & s=3). Repair alternative involves here only finished product families, whereas disassembly and spare parts refurbishing alternative involve finished product as well as materials (component and assembly modules) families.

With the repair alternative, no change is made to the product's original shape. Only unusable materials (s=4) are replaced to restore the product quality level to organization standards. New (s=1) or valorized (s=2) materials can be used as spare parts. Finished products are cleaned. A volume of valorized finished product families (s=2) are thus obtained.

Disassembly alternative is mainly a question of breaking up the volume of recovered product families to obtain a sufficient volume of valorized spare parts to efficiently meet all network needs. Materials in various states are generated from this alternative (s=2, s=3 and s=4). Unusable materials (s=4) are directed towards adequate recycling or clean disposal centers, whereas other materials can be used to feed the network with valorized spare parts (s=2) or can be further disassembled (s=2 and s=3) to generate other materials. This alternative includes some adjustments (repair and/or cleaning) before reintroducing this volume of valorized material into the network.

The volume of valorized product families (s=2) obtained (materials and finished products) are used to answer, partially or completely, needs expressed in the network at service and processing centers. Needs can be filled either with new (s=1) or valorized (s=2). According to service type or processing alternative involved, a portion of needs must be filled only with valorized products.

Volume of reusable products resulting from processing alternatives are termed valorized products (s=2). Volume of recycled or cleanly disposed products (s=4) represent the other result of processing alternatives, since volume of materials dedicated to disassembly (s=3) cannot be used to meet customer needs and can only be further disassembled. If products cannot be further disassembled, they are recycled or cleanly disposed.



* The term product in this figure is used as volume of a product family (finished product and material).

Figure 1.7. Decisions for product sorting at processing centers

1.4. Conclusion and future work

The suggested logistics network reengineering aims at structuring reverse network, while considering supply chain activities. It is inspired by current work on the wheelchairs allocation and valorization context in the Province of Quebec (Canada). Activities related to new product distribution, maintenance, recovery, processing and redistribution are considered. At the end of this reengineering process, a mathematical model is obtained to deal with decisions related to location of recovery and processing centers, distinguished here as valorization centers and recycling or clean disposal centers, as well as warehouses. Decisions relate also to activities allocation. Processing includes repair of finished products, disassembly and spare parts refurbishing as well as recycling or clean disposal. New modeling approaches are proposed to evaluate the impacts of using valorized products as alternative to new products on network performance, from an economic and customer service (material accessibility and delivery delay) point of view.

Service level is evaluated with the modeling of user zones. An approach needs to be developed to locate and forecast services according to user and product family status. Services include demand (acquisition and product replacement) and material recovery (voluntary return and recovery steps undertaken by the organization). New and valorized products can be used in response to demand. Different value and delivery delay can be associated to these two material types, following the implicated sites. It is even considered that a certain proportion of the demand be filled by valorized materials only, according to ultimate consumer requirement or according to established organization policies. For recovery steps, the model aims at determining how collection must be carried out, with the use of private vehicle fleets and/or logistics service providers.

To ensure material flow conservation, a reverse bill of materials is proposed. Probability distribution functions are suggested to consider the fact that different volume of products in various states can be produced from each processing alternative. It is thus possible to reflect the uncertain character of processing products. Processing alternative selection is done on the basis of recovered product family state, but also by considering site capacity, supply, and needs expressed to the network. A greater flexibility is then considered for decisions relating to product volume orientation in reverse networks. Some additional product flow conservation constraints have been proposed to deal with this aspect.

Work has been undertaken to develop methodologies to define processing conditions and user zones as well to forecast services (demand and recovery), following users and products in circulation status. These methodologies and the mathematical model suggested in this article will be validated with data in hand on the wheelchairs context in Quebec.

Although some new modeling approaches are proposed, thus covering new logistics functions neglected until now, others could be considered. Notably, technology selection would be interesting to approach. Resolution complexity of developed models should also represent an exciting challenge for researchers in the coming years.

1.5 Guidelines to practitioners

A methodology for designing logistics networks integrating reverse logistics is suggested. It includes the development of a deterministic mathematical programming model. Two major stakes are raised by this methodology: data collection and processing, and resolution of large-scale problems.

Data collection and processing needed for the definition of all model parameters represent a significant stage of the methodology. It represents nearly up to 70% of all modeling efforts. The quality of the parameters will dictate the quality of location/allocation model decisions. Some data might be difficult to obtain like those related to demand, by distinguishing new and valorized products, recovery and product orientation in network according to their general state. They are not always collected by current information systems. When they are, they cannot be used directly because of lack in standardized processes, notably for sorting and grading, and in follow-up of products lifecycle. Reverse logistics is generally characterized by high uncertainty level regarding quantity, quality, variety and timing of recovery. Information systems and decision-making tools must then be considered not only to ensure data capture, but also to attenuate variability by supporting adequately material flows (Chouinard *et al.*, 2005). Proportions or probability distribution functions that feed the model would thus be establish with more exactitude and precision.

Taking incertitude into consideration while designing logistics networks may require the conversion of determinist model to stochastic model. However, this raises large-scale problems. Recent sampling strategy, notably the sample average approximation (SAA), may be adapted to the proposed model for solving huge number of scenarios (Santoso *et al.*, 2005). It would then be possible to evaluate impact of demand and returns volume, and of product flows orientation, according to their general state, on network configuration.

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1.7 References

Arntzen BC, Brown GG, Harrison TP, Trafton LL, (1995) Global supply chain management at digital equipment corporation. Interfaces, 25(1):69-93.

Ballou RH, (1994) Measuring transport costing error in customer aggregation for facility location. Transportation Journal, 33(3):49-59.

Bloemhof-Ruuward JM, Krikke H, Van Wassenhove LN, (2004) OR models for eco-eco closed-loop supply chain optimization. In: Reverse logistics: Quantitative models for closed-loop supply chain. Springer, 357-379.

Chouinard M, (2003) Système organisationnel et architecture d'un support d'information pour l'intégration des activités de logistique inversée au sein d'un centre de réadaptation. Mémoire de maîtrise, Université Laval, Québec, Canada, accessible at: www.theses.ulaval.ca.

Chouinard M, D'Amours S, Aït-Kadi D, (2005) Integration of reverse logistics activities within a supply chain information system. *Computers in Industry*, 56(1):105-124.

Côté M, Tremblay J, SOM inc. (2003) *Évaluation du projet de valorisation des aides à la locomotion*. Régie de l'assurance maladie du Québec, Québec, Canada.

Ernst R, Cohen MA, (1990) Operations related groups (ORGs): A clustering procedure for production inventory systems. *Journal of Operations Management*, 9(4):574-598.

Fandel G, Stammen M, (2003) A general model for extended strategic supply chain management with emphasis on product life cycles including development and recycling, *IJPE*, 89(3):293-308.

Fleischmann M, (2001) *Quantitative Models for Reverse Logistics*. Springer, Berlin, Germany.

Flores BE, Olson DL, Dorai VK, (1992) Management of multi-criteria inventory classification. *Mathematical and Computer Modeling*, 16(12):71-82.

Geoffrion AM, Graves GW, (1974) Multi-commodity distribution system design by Benders decomposition. *Management Science*, 20(5):822-844.

Guide VDR (2000) Production planning and control for remanufacturing: industry practice and research needs. *Journal of Operations Management*, 18:467-483.

Hillsman EL, Rhoda R, (1978) Errors in measuring distances from populations to services centers. *Annals of the Regional Science Association*, 12:74-88.

Jayaraman V, Patterson RA, Rolland E, (2003) The design of reverse distribution networks: Models and solution procedures. *European Journal of Operational Research*, 150:128-149.

Jayaraman V, Pirkul H, (2001) Planning and coordination of production and distribution facilities for multiple commodities. *European Journal of Operational Research*, 133:394-408.

Krikke H, (1998) *Recovery strategies and reverse logistics network design*. PhD thesis, University of Twente, Enschede, The Netherlands.

Listes O, (2005) A generic stochastic model for supply-and-return network design. *Computers and Operations Research*. Article in press.

Listes O, Dekker R, (2005) A stochastic approach to a case study for product recovery network design. *European Journal of Operational Research*, 160(1):268-287.

Lu Z, Bostel N, (2005) A facility location model for logistics systems including reverse flows: The case of remanufacturing activities. Article in press.

Martel A, (2001) Un modèle général pour l'optimisation de réseaux logistiques. *Proceedings du 4e Congrès international de génie industriel*, 271-280.

Martel A, (2004) Conception et gestion de chaîne logistique. Notes de cours, Université Laval, Québec, Canada.

Ramanathan R, (2005) ABC inventory classification with multiple-criteria using weighted linear optimization. *Computers & Operations Research*, 33:695-700.

Romanowski CJ, Nagi R, Sudit M, (2005) Data mining in a engineering design environment: OR applications from graph matching. *Computers & Operations Research*, 33:3150-3160.
Santoso T, Ahmed S, Goetschalckx M, Shapiro A, (2005) A stochastic programming approach for supply chain network design under uncertainty. *European Journal of Operational Research*, 167:96–115.
Shapiro JF (2001) *Modeling the supply chain*. Duxbury.
Shih L-H (2001) Reverse logistics system planning for recycling electrical appliances and computers in Taiwan. *Resources, Conservation and recycling*, 32:55-72.
Srinivasan M, Moon YB, (1999) A comprehensive algorithm for strategic analysis of supply chain networks. *Computer and Industrial. Engineering*, 36(3):615-633.
Teunter RH (2005) Determining optimal disassembly and recovery strategies. Omega. 34:533-537.
Thierry M, Salomon M, van Nunen J, van Wassenhove L, (1995) Strategic issues in product recovery management. *California Management Review,* 37(2):114-135.

1.8 Appendix

1.8.1 Notation

1.8.1.1 Inferior index

C: Component family set ($c \in C$).
M: Assembly module family set ($m \in M$).
A: Finished product family set ($a \in A$).
P: Product family set ($p \in P = C \cup M \cup A$).
I: New product supplier set ($i \in I$).
J: Service and recovery center set ($j \in J$).
D: User zone set associated to service or recovery center j ($d \in D_j$).
T_j: Set of logistics service providers for recovery associated to service center j ($t \in T_j$).
K: Processing center set ($k \in K$).
R: Recycling and clean disposal center set ($r \in R$).
L: Valorized product warehouse set ($l \in L$).
N: Network unit set ($n \in N = I \cup J \cup D \cup K \cup L$).
U: External network unit set ($u \in U = I \cup D$).
V: Internal network unit set ($v \in V = J \cup K \cup L$).
S: Product family state set ($s \in S$).

1.8.1.2 Superior index

a: Product acquisition demand.
d: Disassembly and refurbishing activity.
e: Recycling or clean disposal activity.
E: Product flows directed toward recycling and clean disposal centers.
LS : Product flows recovered by a logistics service provider.
P : Product flows directed towards valorization centers.
PV : Product flows recovered by a private vehicle fleet.

N: New product family flows required by service centers and processing centers.
nr: Unrecovered product.
r: Product replacement demand.
R: Recovered product family flows following replacement or voluntary return.
re : Repair activities.
rv : Voluntarily returned product.
un: Unused product.
V : Valorized product family flows required by service and processing centers.
w : Storage activities.
z : Processing (repair, disassembly & refurbishing, recycling or clean disposal) and storage activities ($z = d \cup e \cup re \cup w$).

1.8.2 Data

$\mathbf{a_v}$ **:** Fixed cost of using internal network unit v.
$\mathbf{b^z_{psv}}$ **:** Capacity related to product family p in state s of the internal network unit v.
$\mathbf{d^a_{pd}}$**;** $\mathbf{d^r_{pd}}$ **:** Expected demand (acquisition, replacement) for product family p in user zone d.
$\mathbf{f_{psnn'}}$ **:** Unit cost for flow of product family p in state s between node n and n'.
$\mathbf{g_{pp'}}$ **:** Quantity of product family p involved during activities (ass./disassembly) on product family p'.
$\mathbf{h_{pp'}}$ **:** Feasibility to disassemble product family p from p' ($h_{pp'} = 1$ if possible 0 otherwise).
$\mathbf{q_p}$ **:** Size of product family p in standard unit.
$\mathbf{r^r_{psd}}$**;** $\mathbf{r^{rv}_{psd}}$ **:** Expected quantity of product family p recovered in state s from user zone d (replacement, voluntary return).
$\mathbf{v_{psv}}$ **:** Unit processing cost for product family p in state s at the internal network unit v.
$\mathbf{x^{un}_{psd}}$ **:** Expected quantity of unused product family p in state s in user zone d.
$\mathbf{x^{nr}_{psd}}$ **:** Expected quantity of unused products family p in state s not-recovered from user zone d.
$\boldsymbol{\alpha^a_{psd}}$**;** $\boldsymbol{\alpha^r_{psd}}$ **:** Expected minimal demand proportion (acquisition, replacement) for product family p answered with valorized materials (s=2) in user zone d.
$\boldsymbol{\varphi^{re}_{psk}}$**;** $\boldsymbol{\varphi^d_{psk}}$ **:** Expected minimal proportion of product family p to be recycled or cleanly disposed (s=4) following valorization activities (repair, disassembly & refurbishing) at processing center k.
$\boldsymbol{\gamma^{re}_{psk}}$**;** $\boldsymbol{\gamma^d_{psk}}$ **:** Expected maximal proportion of product family p dedicated to disassembly (s=3) generating component or assembly module family which can be reused following valorization activities (repair, disassembly & refurbishing) at processing center k.

1.8.3 Decision variables

$\mathbf{D^a_{psd}}$**;** $\mathbf{D^r_{psd}}$ **:** Demand response (acquisition, replacement) to product family p in state s in user zone d.

F^N_{psiv}; F^V_{pslv} : Quantity of product family p in state s exchanged between supplier i (s=1) or warehouse l (s=2) and one of the internal network units v, specifically service center j or processing center k.

F^R_{psdj}; F^{PV}_{psdj}; F^{LS}_{psdjt} : Quantity of product family p in state s coming from user zone d recovered at service center j (replacement/ voluntary return, private vehicles fleet, logistics service provider t).

$F^E_{psvk'}$: Quantity of product family p dedicated to recycling or clean disposal activities (s=4) directed to internal network unit v, as service center j or processing center k, towards processing center k'.

F^P_{psjk} : Quantity of product family p dedicated to valorization activities (1<s<4) transferred from service center j towards processing center k.

Q^{re}_{psk}; Q^d_{psk}; Q^e_{psk} : Quantity of product family p recovered in state s oriented towards a processing alternative (repair, disassembly & refurbishing, recycling or clean disposal) at processing center k.

V^{re}_{psk}; V^d_{psk} : Quantity of product family p in state s generated during valorization activities (repair, disassembly & refurbishing) at processing center k.

X^{re}_{psk}; X^d_{psk}; X^e_{psk} : Quantity of product family p recovered in state s and processed (repair, disassembly & refurbishing, recycling or clean disposal) at processing center k.

Y_v : Binary variable for opening or not internal network unit v (Y_n=1 if unit is opened and 0 otherwise). Internal network units are processing centers ($k \in K$) and warehouses ($l \in L$).

Z^d_{psk} : Quantity of product family p in state s available for valorization, disassembly or clean disposal following disassembly and refurbishing activities at processing center k.

1.8.4 Mathematical programming model

1.8.5.1 Objective function:

$$CT = \min \sum_{v \in V} a_v Y_v + \sum_{p \in P} \sum_{s \in S} \sum_{v \in V} v_{psv} X_{psv} + \sum_{p \in P} \sum_{s \in S} \sum_{n \in N} \sum_{n' \in N} f_{psnn'} F_{psnn'} \quad (1.1)$$

fixed costs (recovery and processing centers and warehouses) + variable processing costs + material flows costs (handling, storage and transportation) between sites n and n'.

1.8.4.2 Subject to:

<u>Demand constraints:</u>

$$\sum_{s \in S} D^a_{psd} = d^a_{pd} \quad p \in P, 1 \le s \le 2 \quad (1.2)$$

$$\sum_{s \in S} D^r_{psd} = d^r_{pd} \quad p \in P, 1 \le s \le 2 \quad (1.3)$$

Demand response (acquisition, replacements) with new and valorized product family;

$$D^{a}_{psd} \geq \alpha^{a}_{pd}\, d^{a}_{pd} \quad p \in P,\ s=2 \tag{1.4}$$

$$D^{r}_{psd} \geq \alpha^{r}_{pd}\, d^{r}_{pd} \quad p \in P,\ s=2 \tag{1.5}$$

Demand proportion responded with valorized product family, according to customer requirements or organization policies (deterministic approach to establish expected demand response);

$$\sum_{d \in D_j} D^{a}_{psd} + \sum_{d \in D_j} D^{r}_{psd} = \sum_{i \in I} F^{N}_{psij} + \sum_{l \in L} F^{V}_{pslj} \quad p \in P,\ s \in S,\ j \in J \tag{1.6}$$

Demand must be ensured by suppliers (new products) and warehouses (valorized product);

<u>Recovery constraints:</u>

$$d^{r}_{pd} = \sum_{2 \leq s \leq 4} r^{r}_{psd} \quad p \in P,\ d \in D_j \tag{1.7}$$

Product replacement generates expected quantity of recovered product family in various states;

$$r^{r}_{psd} + r^{rv}_{psd} = F^{R}_{psdj} \quad p \in P,\ s \in S,\ d \in D_j,\ j \in J \tag{1.8}$$

Expected quantity of voluntarily returned product family;

$$x^{un}_{psd} - x^{nr}_{psd} - r^{rv}_{psd} - r^{r}_{psd} = F^{PV}_{psdj} + \sum_{t \in T_j} F^{LS}_{psdt} \quad p \in P,\ s \in S,\ d \in D_j,\ j \in J \tag{1.9}$$

Expected quantity of unused product family recovered actively by organization with logistics service providers and private vehicle fleet.

<u>Preliminary product flows orientation constraints (see Figure 1.6):</u>

$$\sum_{d \in D_j} (F^{PV}_{psdj} + \sum_{t \in T_j} F^{LS}_{psdt} + F^{R}_{psdj}) = \sum_{k \in K} F^{E}_{psjk} \quad p \in P,\ s=4,\ j \in J \tag{1.10}$$

Flows of deteriorated product family recovered at each service center are immediately directed to suitable recycling or clean disposal centers;

$$\sum_{d \in D_j} (F^{PV}_{psdj} + \sum_{t \in T_j} F^{LS}_{psdt} + F^{R}_{psdj}) = \sum_{k \in K} F^{P}_{psjk} \quad p \in P,\ 1<s<4,\ j \in J \tag{1.11}$$

Flows of reusable product family are directed to suitable valorization centers;

Elaborated product flows orientation constraints (see Figure 1.7):

$$Q^{re}_{p(s=2)k} + Q^{d}_{p(s=2)k} + Q^{d}_{p(s=3)k} + Q^{e}_{psk} = \sum_{s \in S} \sum_{j \in J} F^{P}_{psjk} \quad p \in P,\ k \in K \qquad (1.12)$$

Product families directed towards each processing alternative, so to valorization and recycling and clean disposal centers, must respect the incoming flows from each service center;

$$Q^{re}_{ask} \leq \sum_{j \in J} F^{P}_{asjk} \quad a \in A,\ s=2,\ k \in K \qquad (1.13)$$

$$Q^{d}_{psk} \leq \Big(\sum_{j \in J} F^{P}_{psjk} - Q^{re}_{psk} \Big) \quad p \in P,\ s=2,\ k \in K \qquad (1.14)$$

$$Q^{d}_{psk} \leq \sum_{j \in J} F^{P}_{psjk} \quad p \in P,\ s=3,\ k \in K \qquad (1.15)$$

Product family quantity directed towards each valorization activity can be lower than incoming flows from service centers;

Disassembly constraints (see Figure 1.7):

$$X^{re}_{psk} = Q^{re}_{psk} + V^{re}_{psk} \quad p \in P,\ s \in S,\ k \in K \qquad (1.16)$$

Product family quantity recovered and processed during repair activities results from product family directed towards repair activities (finished product family) and from product family generated during these same activities (component and module family);

$$Z^{d}_{psk} = Q^{d}_{psk} + V^{d}_{psk} + (Z^{d}_{p(s-1)k} - X^{d}_{p(s-1)k}) \quad p \in P,\ 2 \leq s \leq 4,\ k \in K \qquad (1.17)$$

$$Z^{d}_{p1k}, X^{d}_{p1k} = 0$$

Product family quantity available for disassembly activities for refurbishing, extended disassembly or recycling or clean disposal corresponds to product family directed, generated and downgraded to the corresponding processing alternative;

$$X^{d}_{psk} \leq Z^{d}_{psk} \quad p \in P,\ 2 \leq s \leq 3,\ k \in K \qquad (1.18)$$

Product family quantity actually refurbished or disassembled can be lower or equal to product family quantity made available for these activities;

$$X^{d}_{p(s=4)k} = Z^{d}_{p(s=4)k} \quad p \in P,\ k \in K \qquad (1.19)$$

Product family quantity rejected during disassembly and refurbishing activities is equal to unvalorized product family quantity generated during these activities;

$$h_{pp'}\ g_{pp'}\ X^{re}_{p'sk} = \sum_{2\le s'\le 4} V^{re}_{ps'k} \quad p\in C\cup M,\ p'\in P,\ 1<s<4,\ k\in K \tag{1.20}$$

$$h_{pp'}\ g_{pp'}\ X^{d}_{p'sk} = \sum_{2\le s'\le 4} V^{d}_{ps'k} \quad p\in C\cup M,\ p'\in P,\ s=3,\ k\in K \tag{1.21}$$

Product family dedicated to disassembly during valorization activities generates expected quantities of component or assembly module family in various states;

$$V^{re}_{p(s=2)k} \le \gamma^{re}_{p(s=3)k}\ h_{pp'}\ g_{pp'}\ X^{re}_{p'(s=3)k} \quad p\in P,\ p'\in P,\ k\in K \tag{1.22}$$

$$V^{d}_{p(s=2)k} \le \gamma^{d}_{p(s=3)k}\ h_{pp'}\ g_{pp'}\ X^{d}_{p'(s=3)k} \quad p\in P,\ p'\in P,\ k\in K \tag{1.23}$$

Quantity of product family in good condition generated during valorization activities can be lower or equal to a proportion of product family disassembled during these same activities (deterministic approach to establish expected quantity and state of disassembled product family);

Recycling or clean disposal constraints:

$$V^{re}_{p(s=4)k} \ge \varphi^{re}_{psk}\ h_{pp'}\ g_{pp'}\ X^{re}_{p'sk} \quad p\in C\cup M,\ p'\in P,\ s\in S,\ k\in K \tag{1.24}$$

$$V^{d}_{p(s=4)k} \ge \varphi^{d}_{psk}\ h_{pp'}\ g_{pp'}\ X^{d}_{p'sk} \quad p\in C\cup M,\ p'\in P,\ s\in S,\ k\in K \tag{1.25}$$

Rejected product family generated during valorization activities can be greater than a certain proportion of disassembled product family quantity;

$$\sum_{j\in J} F^{E}_{psjk'} + \sum_{k\in K} F^{E}_{pskk'} = X^{e}_{psk'} \quad p\in P,\ s\in S,\ k'\in K \tag{1.26}$$

All incoming flows in a recycling or clean disposal center represent product family to be processed in these centers;

$$X^{re}_{p(s=4)k} + X^{re}_{c(s=3)k} + X^{d}_{p(s=4)k} + X^{d}_{c(s=3)k} + Q^{e}_{p(s<4)k} = \sum_{k'\in K} F^{E}_{pskk'} \quad c\in C,\ p\in P,\ s\in S,\ k\in K \tag{1.27}$$

Product family rejected during valorization activities are directed to recycling or clean disposal centers.

Materials replacement constraints:

$$X^{re}_{p(s=4)k} = \sum_{i\in I} F^{N}_{psik} + \sum_{l\in L} F^{V}_{pslk} \quad p\in P,\ s\in S,\ k\in K \tag{1.28}$$

Product family rejected during repair activities are replaced by new or valorized product family.

Valorized products supply and demand constraints:

$$X^{re}_{ask} + X^{d}_{psk} = \sum_{l \in L} F^{V}_{pskl} \quad a \in A, p \in P, s=2, k \in K \tag{1.29}$$

Valorized product family generated from valorization activities correspond to product family flows directed to warehouses.

$$\sum_{k \in K} F^{V}_{pskl} = \sum_{v \in V} F^{V}_{pslv} \quad p \in P, s \in S, l \in L \tag{1.30}$$

Flow conservation must be ensured for supply with valorized product family in the network.

Capacity constraints:

$$\sum_{d \in D_j} F^{PV}_{psdj} \leq b^{PV}_{psj} \quad p \in P, s \in S, j \in J \tag{1.31}$$

Private vehicle fleet capacity for each service center must be respected.

$$\sum_{s \in S} X^{re}_{psk} \leq b^{re}_{psk} Y_k \quad p \in P, s \in S, k \in K \tag{1.32}$$

$$\sum_{s \in S} X^{d}_{psk} \leq b^{d}_{psk} Y_k \quad p \in P, s \in S, k \in K \tag{1.33}$$

Valorization centers capacity must be respected.

$$q_p \sum_{k \in K} F^{V}_{pskl} \leq b^{w}_{psl} Y_l \quad p \in P, s \in S, l \in L \tag{1.34}$$

Capacity of valorized product warehouses must be respected.

Restriction of non-negativity:

$$Y_n \in \{0, 1\}, n \in N \tag{1.35}$$

$$F_{psnn'} \geq 0 \quad \forall\ (p, s, n, n') \tag{1.36}$$

$$D_{psn}, Q_{psn}, V_{psn}, X_{psn}, Z_{psn} \geq 0 \quad \forall\ (p, s, n) \tag{1.37}$$