Joint Optimization of Physical and Information Flows in Supply Chains

Jānis Grabis

Riga Technical University, Kalku 1, Riga, LV-1658, Latvia
grabis@rtu.lv

Abstract. Supply chain units are connected by both physical and information flows. Electronic services are used to perform a large part of activities in modern supply chains. The traditional supply chain configuration models pay the main attention to optimization of the physical flows. However, it is equally important to ensure that the physical units have appropriate information processing and logistics capabilities. Therefore, a model for joint configuration of the physical and information flows in e-retailing supply chains is elaborated in this paper. The model simultaneously identifies appropriate suppliers, selects the third party logistics service provider and selects appropriate electronic information processing services. The typical services used in global e-retailing are identified. The services are characterized by their functionality and quality of service measurements. The preliminary experimental studies demonstrate interdependencies between the physical and information flows.

Key words: supply chain, information flow, service selection

1 Introduction

A supply chain is the network of interrelated companies collaborating to serve its customers. It has long been acknowledged that supply chain management concerns with both physical movement of products from suppliers to customers as well as with information flows for synchronizing the supply chain management processes [1]. Meanwhile the distinction between the physical and information flows is becoming less visible in modern supply chains as many supply chain functions are digitalized. Nevertheless, supply chain management methods continue to analyze both flows separately.

This paper attempts to elaborate a supply chain configuration model dealing with both physical and information flows. The supply chain configuration is one of the key supply chain management sub-problems dealing with selection of supply chain units and establishing connections among the units [2]. The joint supply chain configuration implies that the model selects units and establishes the connections to ensure movement of physical goods as well as integrated information processing. The model explores configuration of an e-retailing supply chain, where the e-retailer identifies appropriate suppliers and selects a third-party logistics services provider and simultaneously selects appropriate web services for enabling the information flow in the supply chain. The model combines the traditional supply chain configuration problem [3] with the web service selection problem [4]. The contribution to the field of information logistics is demonstration of mutual interdependencies of the physical supply chain configuration and the web service selection. It is shown that the physical supply chain structure depends upon availability of appropriate information processing services ensuring information integration and information logistics in electronic supply chains.

The paper expands a traditional information sharing approach [5] of studying information flows in supply chain. Klein and Rai [6] suggest that a strategic approach is needed to information integration in supply chains, and Swaminathan and Tayur [7] identifies opportunities for using emerging information technologies in e-business supply chain. Improvements in information logistics is one of options for improving information flows. That is also confirmed by findings that information accuracy and relevance is among the key factors affecting web-site quality in e-business [8]. A hub based approach can be used in integrated the physical and information flows in supply chains [9]. However, in the case of highly distributed and heterogeneous supply chains as in e-retailing, a service oriented approach could be a more attractive option [10].

The rest of the paper is organized as follows. The physical and information flows in the e-retailing supply chain are described in Section 2. These are represented in a form of business process models. These models capture the flows at the strategic level. A mathematical supply chain model for joint optimization of the physical and information flow is formulated in Section 3. Section 4 reports results of the experimental studies conducted to demonstrate interdependencies between the physical and information flows. Section 5 concludes.

2 Supply Chain Flows

A model for joint design of the physical and information flows is developed for supply chains, where a significant part of supply chain activities take place in an electronic form. Supply chains by e-retailers such as Amazon.com, Macy's[1] belong to this group of supply chains. The physical flow represents the flow of products from suppliers to e-retailers facilities and final delivery of products to end-customers usually done by a 3PL provider. The information flow represents different on-line services to customers and supply chain partners. These services include product information services, payment services, insurance services, shipment tracking services and others. The services can be provided by the same partners providing the physical processing or by partners specializing in delivering electronic information processing services. For instance, Borderfree[2] acts as an integrator for e-retailers providing end-to-end information processing services.

[1] http://www.amazon.com, http://www.macys.com
[2] http://www.borderfree.com

2.1 Physical and Internal Information Flow

A business process model is used to represent the physical and information flows and their processing in supply chains. It is assumed that the physical data flow and supply chain units mainly dealing with processing of physical products are represented as a single entity while supply chain units mainly dealing with information processing are represented as independent units. Therefore, the physical supply chain units are represented in the business process as lanes in a single pool (Fig. 1), and the electronic supply chain units are represented as separate pools (see Section 2.2).

The physical flow of products is initiated by detecting the customer demand without specifying how the demand is detected. Suppliers are responsible for supplying the products. The e-retailer is the focal unit in the e-retailing supply chain and its main task is to sell products to customers. The e-retailer can also operate storage and distribution facilities (see [11] on various options for products processing in e-retailing supply chains). The 3PL providers are responsible for delivery of products to the customers. The internal information flow accompanies the physical flow of products. It is referred as to the internal information flow because information processing is perceived as an essential part of the physical products processing tasks. Data objects are used to represent internal supply chain information flows. Only the main data objects such as sales order, purchasing requisition, delivery note and delivery confirmation are referenced in the model. This supply chain representation does not include the reverse supply chain flow for simplicity.

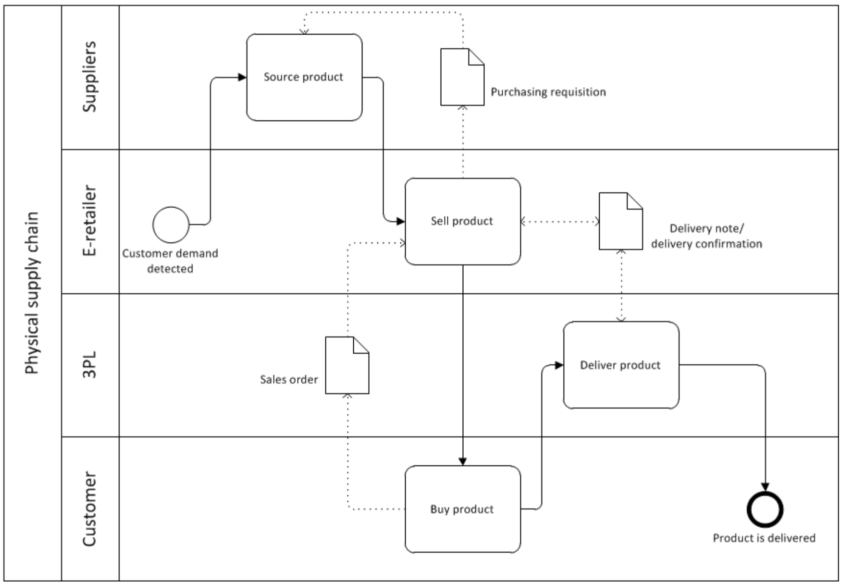

Fig. 1. The physical flow in supply chains

2.2 Message and Integrated Flow

An integrated physical and information flow model is created in order to capture interrelationship among the physical and electronic supply chain units. The electronic supply chain units are represented each in a separate pool named as a service unit with a specific type. These pools represent abstract service providers. The actual service providers can provide several of the services required, some of them act as service aggregators and some services can be provided by the physical supply chain units. The interrelationships are shown as message flows among the pools. The message flow shows only purely electronic information processing activities. For instance, a shipment activity includes shipment data processing, shipment confirmation and other operations but these information processing activities are perceived as an essential part of the physical activities and are included in the Deliver product task.

The model defines main types of the electronic service units present in the e-retailing supply chains in the global setting. These types include:

- Product information services – detailed information possibly aggregated from multiple sources is provided about each product offered by the e-retailer
- Import/export services – checks on import and export restrictions from one country to another for certain products, i.e., the service rejects selling a product in certain countries where specific licensing rules are applicable
- Customs and taxes services – calculation of appropriate taxes depending upon the customer location is performed
- Payment services – multi-currency processing of payments using different payment channels is performed and restrictions concerning availability of the payment channels are applied, e.g., credit cards only from specified countries are accepted
- Shipment services – if multiple shipment modes are available the most appropriate alternative with regards to the destination and delivery time is determined and shipment tracking is provided independently of the 3PL provider is provided, especially, if multiple logistics providers are used for delivery.

The list of service types is not exhaustive and other types of services can be used such as fraud detection and shipment insurance. Fig. 2 shows the physical e-retailing supply chain process along with the necessary electronic services. The expansion of the Buy product task is given in Fig. 3. The message flow for this task is shown only at the sub-process level. The product information service provides information to the Sell product task and is responsible for providing as rich information about the product as possible. The shipment service is invoked during the product delivery to provide opportunities for tracking the product delivery.

Majority of the message flows are associated with the Buy product task. The services are invoked to provide an accurate estimate of the total ordering costs for the customer. For local e-retailers, this operation usually is straightforward but much more comprehensive information should be gathered for global e-retailers. The message flows should ensure information about applicable taxes, import/export restrictions, delivery options and international payment processing. This information is specific to the customer location.

In the given process model it is assumed that the e-retailer manages both the physical and electronic sales process by itself. Another possibility is that a traditional retailer deals only with the physical sales while the electronic part is provided by a sales service provider.

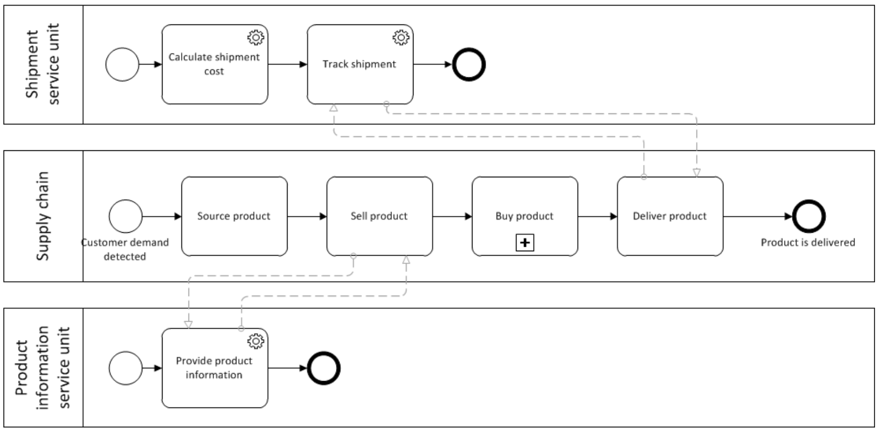

Fig. 2. The message flow between the supply chain and the product information and shipment services

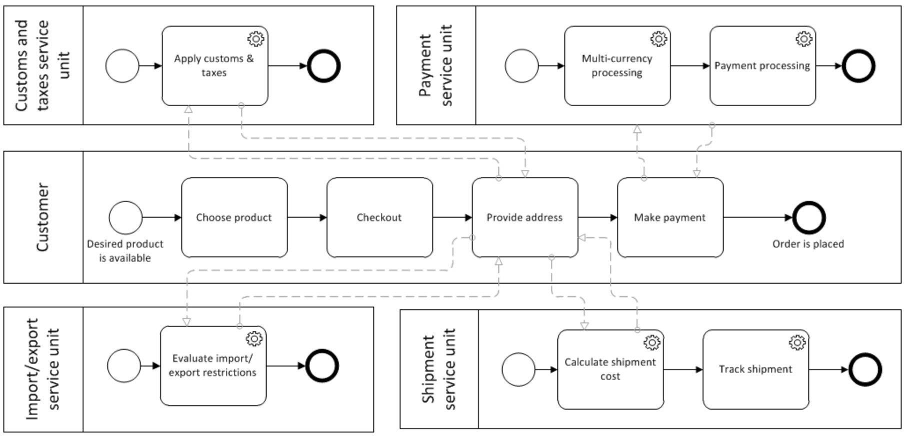

Fig. 3. The message flow for the Buy product task

3 Model

The supply chain business process models show interactions among the physical and electronic supply chain units. The supply chain configuration problem is to select suitable physical and electronic supply chain units to optimize supply chain performance. In the case of e-retailing supply chain, products' suppliers, third party logistic provider and web services for information processing are selected. The supply chain performance is measured by supply chain profitability and customer satisfaction affected by efficiency of information processing. The profitability is calculated as revenues from product sales after deducting sales expenses minus sourcing, delivery and unit setup costs. The information processing efficiency is calculated as a weighted sum of web service Quality-of-Service (QoS) criteria, namely, response time, error rate and reliability, which are among the most frequently used QoS criteria [4].

The mathematical formulation of the model consists of the objective function (Eq. 1) and constraints (Eq. 7-13), the notations used are defined in Table 1. The weights w_1 and w_2 are used to combine the physical units selection and web service selection criteria in a single objective function. Eq. 6 evaluates the information processing efficiency for the selected web services. Importance of the each QoS criteria is determined by the weight factor v_i. Eq. 5 evaluates the fixed cost incurred by incorporating physical or electronic units in the supply chain.

$$P(\mathbf{X}, \mathbf{Y}, \mathbf{Y}) = w_1(R - C_1 - C_2 - C_3) + w_2 L \rightarrow max \tag{1}$$

$$R = \sum_{i=1}^{N_p} \sum_{j=1}^{N_c} \sigma_{ij} S_{ij} \tag{2}$$

$$C_1 = \sum_{i=1}^{N_p} \sum_{j=1}^{N_v} \pi_{ij} Q_{ij} \tag{3}$$

$$C_2 = \sum_{i=1}^{N_p} \sum_{j=1}^{N_l} \sum_{k=1}^{N_c} \delta_{ijk} U_{ijk} \tag{4}$$

$$C_3 = \sum_{i=1}^{N_v} \lambda_i^1 X_i + \sum_{i=1}^{N_v} \lambda_i^2 Y_i + \sum_{i=1}^{N_v} \lambda_i^3 Z_i \tag{5}$$

$$L = \sum_{i=1}^{N_s} \sum_{j=1}^{3} v_j \beta_{ij} Y_i \tag{6}$$

$$S_{ij} \leq d_{ij}, i = 1, ..., N_p, j = 1, ..., N_c \tag{7}$$

$$\sum_{j=1}^{N_l} U_{ijk} \leq S_{ik}, i = 1, ..., N_p, k = 1, ..., N_c \tag{8}$$

Table 1. Notation

Notation	Description
N_p	number or products
N_c	number of countries where customer are located
N_v	number of potential suppliers
N_l	number of potential 3PL providers
N_s	number of potential services
P	e-retailer's profit
$X_i \in \{0, 1\}$	a decision variable indicating whether the ith supplier is selected or not
$Y_i \in \{0, 1\}$	a decision variable indicating whether the ith service is selected or not
$Z_i \in \{0, 1\}$	a decision variable indicating whether the ith 3PL provider is selected or not
S_{ij}	a decision variable determining the quantity of the ith product sold to customer in the jth country
Q_{ij}	a decision variable determining the quantity of the ith product sourced from the jth supplier
U_{ijk}	a decision variable determining the quantity of the ith product delivered by the jth 3PL provider to the kth country
σ_{ij}	revenues from each item of the i product sold in the jth country
π_{ij}	purchasing prices of the ith product from the jth supplier
δ_{ijk}	delivery cost for the ith product by the jth 3PL provide to the kth country
λ_i^1	the setup cost for the ith supplier
λ_i^2	the setup cost for the ith service
λ_i^3	the setup cost for the ith 3PL provider
βij	the value of the jth QoS attribute for the ith service
d_{ij}	demand for the ith product in the jth country
γ_{ij}	equals to one if the ith service supports the jth function and zero if not
τ_{ij}	equals to one if the ith service is available in the jth country and zero if not
M	a large number

$$\sum_{j=1}^{N_c} S_{ij} \leq \sum_{k=1}^{N_v} Q_{ik}, i = 1, ..., N_p \tag{9}$$

$$\sum_{i=1}^{N_s} \gamma_{ij} Y_i = 1, j = 1, ..., N_f \tag{10}$$

$$\sum_{l=1}^{N_p} S_{li} \leq \sum_{k=1}^{N_s} \gamma_{kj} \tau_{ki} Y_k M, i = 1, ..., N_c, , j = 1, ..., N_f \tag{11}$$

$$\sum_{i=1}^{N_p} Q_{ij} \leq X_j M, j = 1, ..., N_v \tag{12}$$

$$\sum_{i=1}^{N_p}\sum_{k=1}^{N_c} U_{ijk} \le Z_j M, j = 1, ..., N_l \tag{13}$$

The constraint Eq. 7 ensures that the sales do not exceed the demand. The sales-delivery balance is enforced by the constraint Eq. 8. The sales-supplies balance is enforced by Eq. 9 stating that the products must be purchased from suppliers in order to sell them to the customers. Eq. 10 specifies that the services should be selected to satisfy all the required information processing functions. The constrains Eq. 11-13 ensure that suppliers, providers and services, respectively, should be included in the supply chain if they perform any activities (e.g., products are supplied by the given supplier). The constraint (12) ties together the physical and information flows by requiring that the products cannot be physically delivered if appropriate information services are not available.

4 Experimental

The experimental studies are conducted to demonstrate interdependencies between physical and information supply chain configuration decisions and to investigate impact of the weights $w_1$and w_2 on the configuration results. In order to check the first aspect, the supply chain configuration is performed without taking into account the information flows (EXP1). Technically, it means that w_2 is set to zero and the constraints (9) and (10) are ignored. The results of EXP1 are compared with an experiment (EXP2) where the physical and information flows are considered simultaneously. It is argued that the joint configuration has a significant impact on supply chain configuration if different suppliers or 3PL providers are selected.

4.1 Design of Experiments

A test supply chain configuration problem is set up for the experimental purposes. The dimensions of this supply chain are given by $N_p = 10, N_c = 30, N_v = 8, N_l = 3$ and $N_s = 10$. The services should provide seven functions. The services vary from highly specialized providing just one function to aggregators providing all functions. Some of the services are available in all countries while others are limited just to selected countries. The demand is randomly generated. However, the average demand for certain products is country dependent, and some supplier are able to produce these cheaper than others. The QoS characteristics are also randomly generated thought they are correlated with a number of functions the service provides (i.e., than more functions than worse performance). The model is solved using a commercially available mathematical programing software.

4.2 Results

The experiments EXP1 and EXP2 are carried out for the test supply chain. Fig. 4 shows all supply chain unit evaluated during the configuration and the units selected are shaded. $P' = R - C_1 - C_2 - C_3$ measures the supply chain performance in each experiments. It can be observed that different supply chain configurations are obtained in both experiments. In EXP1, the supply chain is able to serve all customers. The electronic information flows are provided by a combination of three web services and a 3PL provider, which provides more uniform delivery costs around the world, is selected. In EXP2, the information processing is performed by a single aggregator, which covers all but four countries. One additional supplier is present in the results of EXP1 compared to the results of EXP2. This supplier is able to supply all products but it specializes in the products most frequently order by the customers in the countries not served in EXP2. The supply chain performance is substantially affected by taking into account interdependencies between the physical and information flows for the given test supply chain.

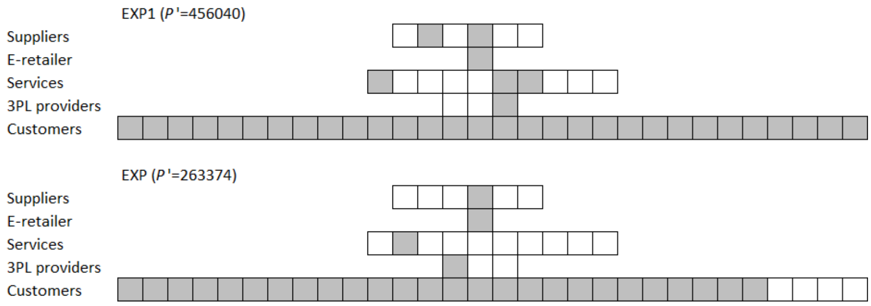

Fig. 4. The supply chain configurations obtained in experiments EXP1 and EXP2

The relative value of the weight factor w_2 characterizing the importance of QoS criteria in optimization is varied in order to evaluate sensitive of the results. The test supply chain used in the paper is quite insensitive to this factor. The QoS criteria had significant impact on the configuration results only for values w_2 exceeding 10^5 (the cost related factors and quality related factors have vastly different scales).

5 Conclusion

A model for joint optimization of the physical and information flows in e-retailing supply chains has been elaborated. The model ensures that the physical supply chain units have appropriate information processing capabilities at their disposal. The importance of the joint optimization increases along with a growing number of electronic services available over the Internet.

The formulated optimization model defines relationships between the physical and information flows and takes into account QoS requirements for efficient information processing. Preliminary experimental results show that the information flows indeed affect selection of appropriate physical supply chain units.

However, the QoS requirements have minor impact of the supply chain configuration decisions for the test supply chain analyzed in the paper. An alternative approach to including QoS criteria directly in the objective model would specification of minimum quality requirements in the form of constraints. That would also alleviate the problem of selecting appropriate weights for multi-criteria optimization. The QoS characteristics also have impact on customer demand what could also be represented in the optimization model.

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