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Multi-objective global supply chain design

- a dynamic model including cash flow, cycle time, carbon foot print and international trade aspects

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ABSTRACT

Designing supply chains is a strategic task that may generate – or destroy – competitive advantage. Discussing global supply chains inevitably implies focusing the flow of physical goods, of information, and of money across international borders. Consequently, numerous country- and location-specific factors as well as aspects of international trade have to be taken into account, since they significantly influence the overall performance level of the supply chain. Recent discussions about the carbon footprint along the supply chain demands to consider ecological issues when designing value networks. Most supply chain design approaches are focused on financial measures, such as profit, only. Other performance measures, e.g. quality, flexibility, or time, are most often neglected in these models.

In this paper we present a global supply chain design model using a multi-objective approach. Besides a financial measure (free cash flow), we address both cycle time and carbon footprint as further objectives. Incorporating delivery time is crucial in many real-life environments where time is of high relevance regarding responsiveness to customer orders, where product

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life-cycles are very short, or where long transport times should be avoided in order to reduce risks. We introduce a set of essential factors that are relevant when materials and products are exchanged between different countries. Other supply chain design models incorporate only a subset of these factors, thus neglecting crucial parameters of the planning problem. We transform our multi-objective supply chain design problem into a single-objective approach by applying the ε- constraint method.

Keywords: Supply chain design; Global; Multi-objective; Cycle time; Carbon footprint; international trade

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1. INTRODUCTION

From the beginning of the 1990s, when Eastern European markets, China and India became more and more accessible, companies located in the western world not only developed these regions as new sales markets but also recognized that attractive new low cost manufacturing locations were in reach. These new emerging markets and the new competitors located in these geographies were beginning to put a threat on producers in Europe and North America during the last ten years. Consequently, many firms expand their business operations into these regions as part of their globalization strategy. In this context, decisions about where to locate manufacturing facilities and other “hardware” of the value chain are of outstanding importance. This global map of the firm’s facilities and related flows of goods cannot be developed without considering both the supply and the sales markets. Designing the global supply chain constitutes a major competitive factor and is fundamental to the competitive strategy of the firm. Due to the complexity of the problem associated with supply chain design, there is growing need for advanced models and for efficient solution procedures that support decision makers.

In this paper we present a global supply chain design model that is based on the multi-objective optimization approach and that considers a financial measure (free cash flow to the firm) as well as non-financial measures (cycle time and carbon footprint) as objectives. By including cycle time we are able to model the time-based responsiveness of the supply chain, which is crucial in many real-life environments. Adding carbon footprint to the model makes sure that legal as well as customers' requirements and voluntary ecological objectives can be taken into account. In the following section, we give a short introduction and definition of global supply chain design. Based on the literature, section 3 gives a short overview of existing multi-objective optimization models for the supply chain design problem that consider country-specific factors. Section 4 presents our model and in the last section, we give a short summary and provide some ideas for further research.

2. GLOBAL SUPPLY CHAIN DESIGN

2.1 Definition

The dynamics of the worldwide business environment force companies to redesign their supply chains rather frequently. Firms have to react to changing conditions regarding sales volumes, labor costs and availabilities as well as the attractiveness of supply markets. Switching to new suppliers, setting up new facilities, relocating or closing existing ones, and entering new sales markets is daily business, at least for larger global players. Globalization and the mergers and acquisitions frenzy are further reasons why redesigning the supply chain becomes inevitable and happens more frequently in practice (GOETSCHALCKX, 2000). We define supply chain design as the decision process that structures the company's supply chain on a mid to long term perspective (CHOPRA ET AL., 2004). This process includes decisions about the number and the location of the firm's facilities, about production techniques to be implemented and the output-related capacity of each facility, about assigning geographical markets to these facilities, and the selection of (worldwide) suppliers that provide manufacturing facilities with needed sub-assemblies, components, and materials. Thus, the entire value chain of the firm – sourcing, material deliveries, manufacturing and distribution of finished goods – is affected by supply chain design decisions (HUCHERZERMEIER ET AL., 1996). Typically, the planning horizon for these decisions ranges from three to ten years. Consequently, supply chain design decisions are strategic in character since they influence the long-term profitability and competitive position of the firm to a large extent (GOETSCHALCKX, 2000). Therefore, supply chain design addresses the fundamental structure of the value network that is usually not changed from one day to the other. However, short-term adaptations are common, but only seldom change the fundamental structure of the supply chain significantly.

In order to reduce complexity, rather aggregated data is required for basic design decisions. Developments in time regarding prices, market demands, cost factors, exchange rates, etc. are hard to estimate. Consequently, the robustness of the solution delivered by the model has to be proven. Existing models address the problem of uncertainty by applying stochastic approaches (HODDER ET AL., 1986, HUCHZERMEIER ET AL., 1996), fuzzy optimization (SAKAWA ET AL., 2001), or scenario techniques (FLEISCHMANN ET AL., 2006).

2.2 Country-specific factors

In addition to factors incorporated in single-country models, global supply chain design models that take a holistic approach have to consider the following aspects that influence cost and performance of the designed structure (COHEN ET AL., 1989): duties and tariffs, duty drawbacks, local content rules, offset trade, currency exchange rates, country-specific tax rates, and transfer price mechanisms. Our approach covers all above mentioned aspects.

Although there is strong tendency towards free trade in the world, protectionist policies are common – even in developed countries – in order to protect single economies and trading zones such as NAFTA, EU, or Mercosur. Duties are ranked among tariff trade barriers that have also to be considered if goods are shipped between different national or multinational trading zones. Recoveries of duties – so called duty drawbacks or duty avoidances – can be of significant financial value and should be taken into account, if

(i) a product is imported and subsequently exported without change (duty drawback for re-export in the same condition),

(ii) a product is imported and e.g. then incorporated into a subassembly, thus performing value-adding tasks, and the subassembly is re-exported (duty drawback for re-export in a different condition),

(iii) a product is exported and later re-imported as part of a larger assembly (duty avoidance for domestic goods returned in a different condition) (ARNTZEN ET AL., 1995).

For US companies estimates of unclaimed duty drawbacks range from USD 1.5 to 10 billion per year (OH and KARIMI, 2006). To the best of our knowledge no model has been published yet that properly models duty drawbacks along the entire supply chain (from the source of the raw materials to the focused company further on to the customer).

Non-tariff trade barriers have major influence on the optimal structure of the supply chain, especially local content rules and offset trade. Developing countries often impose local content requirements (LCRs) for goods to be produced in the country, thus trying to raise local employment and to enhance technology transfer to their country. LCRs usually refer to either the volume or the value of the goods produced in a certain country. Volume-based LCRs define a certain fraction of the total number of components or raw materials used as inputs in the manufacturing process of the final good that must be of domestic origin. Since this physical content protection scheme is only adequate when the input materials are relatively homogeneous, LCRs in terms of value are prevalent in industries where materials differ in complexity and value. Value-based LCRs refer to the money value of components and raw materials of domestic origin that must be at least as large as a specified percentage of either the value of all purchased parts or of the final good’s value (MUNSON ET AL., 1997). Offset agreements are very similar to LCRs. They require the seller of products in a certain country (without necessarily having a plant there) to spend some percentage of the sales volume for buying goods in that country over a specified period of time (MONCZKA ET AL., 2005).

When designing a global supply chain, the decision maker also has to consider varying currency exchange rates. The profit situation of a company can be heavily influenced when buying or selling goods in different currencies without hedging. Some companies try to minimize their currency risk by natural hedging, they try to balance annual revenues and expenditures in the respective currency areas (BROLL, 1992).

Tax rates that are imposed on profits may differ from country to country. This factor could be addressed in a global supply chain model as well. In this context, transfer prices between business units have to be considered as they strongly influence profits of foreign subsidiaries. Transfer prices may be used as a tool for shifting profits between different units in order to avoid high tax payments. However, these measures have to be according to the law and they are under careful observation of tax authorities (VIDAL ET AL., 2001).

2.3 Carbon footprint design

Environmental consciousness becomes more and more critical in the design of supply chain networks. On the one hand customers' buying behavior depends more and more on ecological aspects such as carbon footprint. On the other hand a wide range of legal regulations that differ from country to country, sometimes from state to state, heavily imposes restrictions on the manufacturing processes. A growing body of literature focusing green supply chain management (see e.g. BOWEN ET AL., 2001; VACHON ET AL. 2006), socially responsible purchasing (see e.g. CARTER ET AL., 2002; CARTER, 2004) or closed-loop supply chains (see e.g. SEITZ ET AL., 2004; GUIDE ET AL., 2009) has picked up issues on how to integrate environmental as well as sustainable thinking into supply chain management (KRAUSE ET AL., 2010). Green supply chain management aims at reducing waste and pollution, at saving energy, conserving natural resources, and reducing carbon emissions. Many companies are particularly sensitive to reduce their carbon emissions, since this topic is intensively discussed in the media as the major reason for climate change. Furthermore, consumers are getting more and more concerned about their private carbon footprint. Some industries, like retail or food industry seem to be more aware of this change than others (HOFFMAN, 2007). Literature about strategic supply chain management is scarce with respect to modeling carbon emissions (NETO ET AL., 2009; SUNDARAKANI ET AL., 2010). We found no model for global supply chain network design problems that takes a holistic approach and that includes environmental aspects in the literature.

2.4 Supply Chain Performance Measures

Before developing and applying a global supply chain design model, a decision maker has to define appropriate measures to evaluate the performance of the supply chain. Although cost-focused or profit-related performance measures are dominant in the literature for formal supply chain design models, many other measures can be taken into account as well. As business strategy and supply chain design should be harmonized (SODHI, 2003; CHOPRA ET AL., 2004), using cost or profit measures only might not be sufficient. Performance measures to evaluate the effectiveness and the efficiency of supply chains can be differentiated into qualitative and quantitative measures. For qualitative ("soft") measures, such as customer satisfaction or product quality (BISWAS ET AL., 2004), determining the direct effects on costs and profits is difficult, sometimes virtually impossible. Accordingly, these measures are usually not applied in quantitative (numerical) supply chain design models (BEAMON, 1998). Quantitative performance measures can be described numerically without prior transformation and can therefore be easily integrated into quantitative supply chain design decisions. As shown in table 1, these measures can be differentiated into: (i) financial measures and (ii) non-financial measures (BISWAS ET AL., 2004).

Financial performance measures:	cost (Rosenfield, 1996), sales (Hammel et al., 1993), profit (Cohen et al., 1989), return on investment, net present value (Fleischmann et al., 2006)
Non-financial performance measures:	cycle time (Arntzen et al., 1995), flexibility (Voudouris, 1996), asset/resource utilization, customer service level, environmental quality (Neto et al., 2009)

Table 1: Quantitative supply chain performance measures

3. LITERATURE REVIEW

Since the model presented below includes financial as well as non-financial measures, this literature review is focused on two aspects only (see table 2): (1) country-specific factors considered in global supply chain design models, and (2) performance measures used in the objective function(s). For a recent and more comprehensive review of the literature related to global supply chain design see Melo et al. (2009).

Author		Hodder and Dincer (1986)	Cohen and Lee (1989)	Arntzen et al. (1995)	Voudouris (1996)	Sabri and Beamon (2000)	Vidal and Goetschalckx (2001)	Guillén et al. (2004)
international factors	Exchange rates	x	x				x	
	Duties	x	x	x		x	x	
	Local content			x				
	Offset trade		x	x				
	Taxes	x	x	x			x	(x)
	Transfer prices		x				x	
performance measures/ objectives	Cost			x		x		
	(Discounted) Profit	x	x				x	
	Net present value of the yearly cash flows							x
	Customer responsiveness					x		
	Activity time (production + transportation time)			x				
	Flexibility				x	x		
	Demand satisfaction							x
	Financial risk							x

Table 2: Literature Overview

Hodder and Dincer (1986) presented an early and influential paper about supply chain design models that also consider country-specific factors. Their single-period model maximizes profit and considers exchange rates, duties, and taxes. Cohen and Lee (1989) considered offset trade and transfer prices in their model. The non-linear objective function of the model is targeted at after-tax profits, including both tariffs and transfer prices, and is therefore hard to solve for (larger) real-life problems. Arntzen et al. (1995) developed the first multi-objective supply chain design model by considering costs as well as time in their objective function. In their approach cost terms are weighted by α, and time terms by (1-α). However, assigning weighting factors before optimization constitutes a decision problem itself and implies repetitive runs of the model with varying values for α. Another valuable contribution of this work is the consideration of local content and offset trade constraints. VOUDOURIS (1996) is one of the few authors who explicitly addresses flexibility in the objective function. Flexibility is expressed numerically as it is assumed to be associated with the level of slack that absorbs unexpected demand related to the resource constraints. However, the model does not take into account country-specific factors.

SABRI and BEAMON (2000) developed a multi-objective decision model that includes cost, customer service level and flexibility. In their solution procedure, the ε-constraint method (HAIMES ET AL., 1971) is applied. The basic idea of this method is to transform the multi-objective problem into a single-objective optimization problem by maximizing one of the objective functions – or minimize it, respectively – while defining the other objectives as constraints with given values $\varepsilon_1, ..., \varepsilon_{n-1}$. Regarding country-specific factors, this model only considers duties. VIDAL and GOETSCHALCKX (2001) present a heuristic for a non-convex supply chain design optimization problem with a linear objective function and linear as well as bilinear constraints. The model considers exchange rates, duties, taxes, and transfer prices.

GUILLÉN ET AL. (2004) designed a multi-objective decision model, which considers net present value (NPV), demand satisfaction and financial risk as objectives. They also utilize the ε-constraint method to solve their problem. Country-specific factors are not addressed and only a single uniform tax rate is considered in their approach.

Literature is scarce of models considering ecological aspects for designing supply chains. NETO ET AL. (2009) present an algorithm for the visual representation of a Pareto-optimal frontier balancing economic value and environmental quality of a logistics network. However their model focuses the design of material flows within recycling operations.

SUNDARAKANI ET AL. (2010) focus on measuring carbon footprint within a supply chain network, while the supply network design itself is not part of the analysis.

Reviewing literature we did not find a single global supply chain design model that addresses country-specific factors in a comprehensive manner and that supports multi-objective decision making (see also table 2). We develop a multi-objective global supply chain design model that incorporates several country-specific factors that we rate as being essential for global supply chain design as well as carbon emissions.

4. MODEL DESCRIPTION

The Mixed Integer Linear Programming (MILP) model is based on the following assumptions:

1. There is a finite number of potential supply markets and production facilities (discrete model).

2. The planning horizon covers several periods (e.g. years).

3. All data is deterministic.

4. Demands of sales regions have to be fulfilled to full extent. The demand per period is assumed to be constant. A pre-defined maximum cycle time may not be exceeded.

5. Sales prices are fixed and cannot be influenced.

6. Capacities of supply markets / suppliers and production sites are restricted.

7. Transport costs are proportional to transport distance, amount and weight of the transported goods.

8. The multi-echelon production process has no loops and is convergent.

9. Customers are delivered directly from the production site that finishes the last production step. Nevertheless distribution centers can be modeled as additional production sites.

10. Inventory costs for work in progress accrue for goods during production and transportation processes.

Supply chain design decisions can be differentiated into two layers (see chart 1): The structure of the supply chain regarding locations, facilities, resources, and processes and the material flow between these structural entities is of concern. Facilities f can be opened and resources r – machines and equipment – have to be installed. Production processes p at the respective facility require certain resources. The amount and type of installed resources determine the capacity of the respective facility. Material flows run from suppliers to facilities tas_{sflmct}, inside facilities measured by production amounts pra_{frpct}, as inbound material flows within one facility or between different facilities tai_{fglpct} as well as outbound material flows from the facilities to the customers tac_{fclxt}.

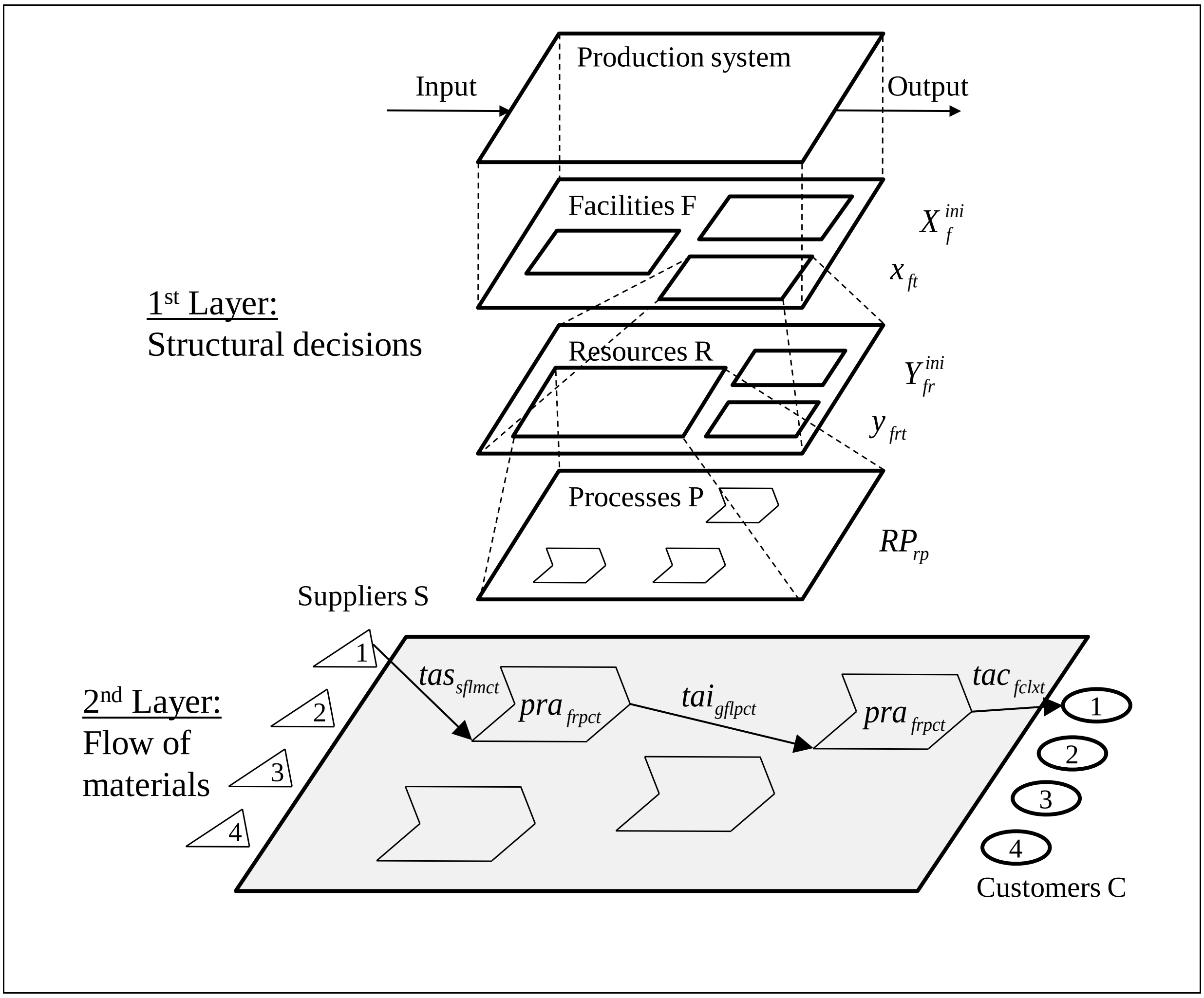

Figure 1: Layers of the decision problem

4.1 Objective function

We maximize the Free Cash Flows to the Firm (FCFF) discounted by using weighted average cost of capital (WACC) (DAMODARAN 2001). The FCFF is determined by subtracting capital investments and tax payments from the EBITDA (earnings before interest, taxes, depreciation and amortization). Since depreciations have the effect to decrease tax payments, this effect also has to be considered when determining FCFF by adding a correction factor (see figure 2).

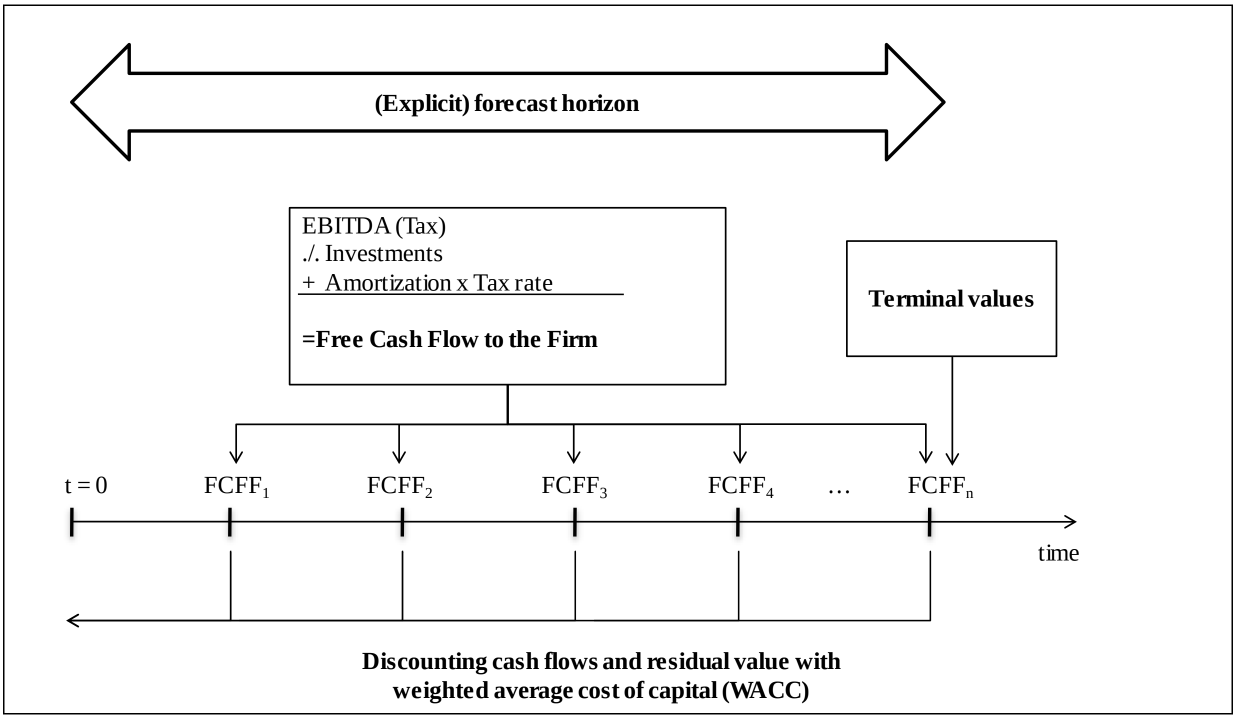

Figure 2: Discounted Cash Flow method (DAMODARAN, 2001)

Assuming a limited planning horizon, we introduce the variable tv_a indicating the terminal value of assets. The terminal value tv_a as well as Free Cash Flows $fcff_{at}$ for each country a and each period t are given in the respective currency and are transferred into "home" currency values by $1/ERH_{at}$.

$$\max\left(\sum_{a\in A}\sum_{t\in T}\frac{fcff_{at}}{ERH_{at}}\cdot\frac{1}{(1+WACC)^t}+\sum_{a\in A}\frac{tv_a}{ERH_{aT}}\cdot\frac{1}{(1+WACC)^t}\right) \tag{1}$$

As described above FCFF can be calculated as follows:

$$fcff_{at}=ebitda_{at}\cdot(1-Tax_{at})+dep_{at}\cdot Tax_{at}-capEx_{at} \quad \forall\, a\in A, t\in T \tag{2}$$

Calculation of components of equation (2) is done within the next steps. First the EBITDA is calculated for each country and each period:

$$ebitda_{at} =$$

$$\sum_{f\in F_a}\sum_{c\in C}\sum_{l\in L}\sum_{x\in X} tac_{fclxt}\cdot\frac{PrX_{cxt}}{ER_{ab(c)t}}+\sum_{f\in F_a}\sum_{\substack{g\in F\\ g\notin F_a}}\sum_{l\in L}\sum_{p\in P}\sum_{c\in C} tai_{fglpct}\cdot TP_{pt}\cdot ERH_{at}$$

(Turnover with final customers + internal turnover)

$$+\,closeC_{at}$$

(Costs of restructuring)

$$-\sum_{s\in S}\sum_{f\in F_a}\sum_{l\in L}\sum_{m\in M}\sum_{c\in C} tas_{sflmct}\left(\frac{PrM_{smt}}{ER_{ab(s)t}}+DistSF_{sf}\cdot WM_{m}\cdot CT_{lt}\cdot ERH_{at}\right)$$

(Material cost + transportation cost)

$$-\sum_{m\in M}\sum_{\substack{b\in A\\ b\neq a}}\sum_{c\in C} dutyValueM_{mbact}\cdot DutyRateM_{mbat}$$

(Duties for materials)

$$-\sum_{\substack{f\in F\\ f\notin F_a}}\sum_{g\in F_a}\sum_{l\in L}\sum_{p\in P}\sum_{c\in C} tai_{fglpct}\cdot TP_{pt}\cdot ERH_{at}$$

(Costs for internal deliveries (intercompany deliveries))

$$-\sum_{p\in P}\sum_{\substack{b\in A\\ b\neq a}}\sum_{c\in C} dutyValueP_{pbact}\cdot DutyRateP_{pbat}$$

(Duties for semi - finished products)

$$-\sum_{f\in F}\sum_{g\in F_a}\sum_{l\in L}\sum_{p\in P}\sum_{c\in C} tai_{fglpct}\cdot DistFF_{fg}\cdot WP_{p}\cdot CT_{lt}\cdot ERH_{at}$$

(Transportation costs for internal deliveries (intercompany deliveries))

$$-\sum_{f\in F_a}\sum_{r\in R}\sum_{p\in P}\sum_{c\in C} pra_{frpct}\cdot PC_{frpt}$$

(Variable production costs)

$$-\sum_{p\in X}\sum_{\substack{b\in A\\ b\neq a}}\sum_{c\in C} dutyValueX_{xabct}\cdot DutyRateX_{xabt}$$

(Duties for final products)

$$-\sum_{f\in F_a}\sum_{c\in C}\sum_{l\in L}\sum_{x\in X} tac_{fclxt}\cdot DistFC_{fc}\cdot WX_x\cdot CT_{lt}\cdot ERH_{at}$$

(Transportation costs for final products)

$$-\,inventCC_{at}$$

(Inventory costs)

$$-\sum_{f\in F_a} FixCF_{ft}\cdot x_{ft}-\sum_{f\in F_a}\sum_{r\in R} FixCR_{frt}\cdot y_{frt}$$

(Fixed costs for facilities and resources) (3)

$\forall$ a $\in$ A, t $\in$ T

In order to determine EBIDTA inventory carrying costs are calculated applying equation (4).

$$\begin{aligned}
inventCC_{at} &= \sum_{f\in F_a}\sum_{r\in R}\sum_{p\in P}\sum_{c\in C} pra_{frpct}\cdot TP_{pt}\cdot PT_{frpt}\cdot\frac{1}{360}\cdot ERH_{at}\cdot InvCC_t\\
&+\sum_{f\in F}\sum_{g\in F_a}\sum_{l\in L}\sum_{p\in P}\sum_{c\in C} tai_{fglpct}\cdot\frac{DistFF_{fg}}{TS_l}\cdot\frac{1}{360}\cdot TP_{pt}\cdot ERH_{at}\cdot InvCC_t\\
&+\sum_{f\in F_a}\sum_{c\in C}\sum_{l\in L}\sum_{xX} tac_{fclxt}\cdot\frac{DistFC_{fc}}{TS_l}\cdot\frac{1}{360}\cdot\frac{PrX_{cxt}}{ER_{ab(c)t}}\cdot InvCC_t
\end{aligned}\tag{4}$$

$$\forall a\in A, t\in T$$

It is assumed that cash flows CCR_{frt} and CCF_{ft} result from de-investing resources or closing down entire facilities. The respective cash flows result from:

- Payouts due to severance payments for discharged employees.
- Payouts due to premature redemption of contracts.
- Payments from selling assets.
- Payouts due to disposal and recycling of assets.

Costs for closing a resource or facility are calculated by equation (5).

$$closeC_{at} = \sum_{f \in F_a} \sum_{r \in R} CCR_{frt} \cdot closeR_{frt} + \sum_{f \in F_a} CCF_{ft} \cdot closeF_{ft} \qquad (5)$$
$$\forall\, a \in A, t \in T$$

Inequations (6) to (8) ensure, that the binary decision variable $closeR_{frt}$ takes the value 1 only in case the resource was used in previous periods and is closed in period t.

$$0 \geq \begin{cases} -Y_{fr}^{ini} + closeR_{frt} & \text{if } t = 1 \\ -y_{fr(t-1)} + closeR_{frt} & \text{if } t \neq 1 \end{cases} \qquad (6)$$
$$\forall\, f \in F, r \in R, t \in T$$

$$0 \geq -(1 - y_{frt}) + closeR_{frt} \qquad \forall f \in F, r \in R, t \in T \qquad (7)$$

$$1 \geq \begin{cases} -Y_{fr}^{ini} + (1 - y_{frt}) - closeR_{frt} & \text{if } t = 1 \\ -y_{fr(t-1)} + (1 - y_{frt}) - closeR_{frt} & \text{if } t \neq 1 \end{cases} \qquad (8)$$
$$\forall\, f \in F, r \in R, t \in T$$

Inequations (9) to (11) make sure, that $closeF_{ft}$ is a binary decision variable .

$$0 \geq \begin{cases} -X_{f}^{ini} + closeF_{ft} & \text{if } t = 1 \\ -x_{f(t-1)} + closeF_{ft} & \text{if } t \neq 1 \end{cases} \qquad (9)$$
$$\forall\, f \in F, t \in T$$

$$0 \geq -(1 - x_{ft}) + closeF_{ft} \qquad \forall f \in F, t \in T \qquad (10)$$

$$1 \geq \begin{cases} -X_{f}^{ini} + (1 - x_{ft}) - closeF_{ft} & \text{if } t = 1 \\ -x_{f(t-1)} + (1 - x_{ft}) - closeF_{ft} & \text{if } t \neq 1 \end{cases} \qquad (11)$$
$$\forall\, f \in F, t \in T$$

Calculating FCFF in equation (3) requires determination of depreciations dep_{at} for each country a and each period t, see equation (12).

$$dep_{at} = \sum_{f \in F_a} DepF_{f} \cdot x_{ft} + \sum_{f \in F_a} \sum_{r \in R} DepR_{fr} \cdot y_{frt} \qquad (12)$$
$$\forall\, a \in A, t \in T$$

Capital expenditure for investments is calculated in an aggregate manner for facilities and resources in equation (13).

$$capEx_{at} = \sum_{f \in F_a} investF_{ft} + \sum_{f \in F_a} \sum_{r \in R} investR_{frt} \qquad (13)$$
$$\forall\, a \in A, t \in T$$

Inequality (14) determines investments into resources. Non-negativity constraint (48) ensures that no negative investments are possible.

$$investR_{frt} \geq \begin{cases} InvR_{frt} \cdot \left(y_{frt} - Y_{fr}^{ini}\right) & \text{if } t = 1 \\ InvR_{frt} \cdot \left(y_{frt} - y_{fr(t-1)}\right) & \text{if } t \neq 1 \end{cases} \qquad (14)$$
$$\forall\ f \in F, r \in R, t \in T$$

Investments into facilities are considered by inequality (15).

$$investF_{ft} \geq \begin{cases} InvF_{ft} \cdot \left(x_{ft} - X_{f}^{ini}\right) & \text{if } t = 1 \\ InvF_{ft} \cdot \left(x_{frt} - x_{f(t-1)}\right) & \text{if } t \neq 1 \end{cases} \qquad (15)$$
$$\forall\ f \in F, t \in T$$

As discussed above terminal values of assets are determined at the end of the planning horizon. Equation (16) summarizes terminal values for each country regarding facilities tvf and resources tvr installed at the facilities.

$$tv_a = \sum_{f \in F_a} tvf_f + \sum_{f \in F_a} \sum_{r \in R} tvr_{fr} \qquad \forall\ a \in A \qquad (16)$$

The terminal value of a facility yields from the difference of the investments needed to open that facility and depreciations till the end of the planning horizon. To ensure that the terminal value is always positive, a non-negative constraint (55) is introduced.

In case a facility is opened at $t = 0$, an initial value IVF_f for this investment has to be defined.

$$tvf_f \leq IVF_f \cdot X_f^{ini} + \sum_{\substack{t \in T \\ t = 1}} InvF_{ft} \cdot \left(x_{ft} - X_f^{ini}\right) + \sum_{\substack{t \in T \\ t \neq 1}} InvF_{ft} \cdot \left(x_{ft} - x_{f(t-1)}\right) - \sum_{t \in T} DepF_f \cdot x_{ft} \qquad (17)$$
$$\forall\ f \in F$$

To make sure that only facilities f, that are active in the last Period T, have positive terminal values, inequation (18) is introduced.

$$tvf_f \leq BigM \cdot x_{ft} \qquad \forall\, f \in F, t \in T \qquad (18)$$

Inequations (19) and (20) determine the terminal values of the resources.

$$tvr_{fr} \leq IVR_{fr} \cdot Y_{fr}^{ini} + \sum_{\substack{t \in T \\ t = 1}} InvR_{frt} \cdot \left(y_{frt} - Y_{fr}^{ini}\right) + \sum_{\substack{t \in T \\ t \neq 1}} InvR_{frt} \cdot \left(y_{frt} - y_{fr(t-1)}\right) - \sum_{t \in T} DepR_{fr} \cdot y_{frt} \qquad (19)$$
$$\forall\ f \in F,\ r \in R$$

$$tvr_{fr} \leq BigM \cdot y_{frt} \qquad \forall f \in F, r \in R, t \in T \tag{20}$$

4. 2 Constraints

Material Flows

Customers‘ demands Dem_{cxt} for every product have to be fulfilled in each period (21):

$$\sum_{f \in F} \sum_{l \in L} tac_{fclxt} = Dem_{cxt} \qquad \forall c \in C,\ x \in X,\ t \in T \tag{21}$$

Equation (22) guarantees that finished products delivered from the respective facility have been processed through all relevant manufacturing steps.

$$\sum_{l \in L} tac_{fclxt} = \sum_{r \in R} pra_{frpct} \qquad \forall\ f \in F,\ c \in C,\ x \in X,\ p \in EP_{x,}\ t \in T \tag{22}$$

The amount of materials and semi-finished products delivered to a facility have to match the requirements for producing the amount of both finished and semi-finished products to be delivered from this facility to the customers. Equation (23) makes sure that the required amount of semi-finished products is supplied BoP_{qp} specifies the preceding production step q for each step p:

$$\sum_{r \in R} \sum_{p \in P} pra_{frpct} \cdot BoP_{qp} = \sum_{g \in F} \sum_{l \in L} tai_{gflqct} \qquad \forall\ f \in F, p \in P, c \in C, t \in T \tag{23}$$

Supplying facility f from location g with semi-finished product q requires that the needed amount of semi-finished products is manufactured at location g (24):

$$\sum_{r \in R} pra_{grqct} = \sum_{f \in F} \sum_{l \in L} tai_{gflqct} \qquad \forall\ g \in F, q \in P, q \notin EP, c \in C, t \in T \tag{24}$$

Furthermore, the required materials m, sourced from external suppliers have to be taken into account. BoM_{pm} defines how many items of material m are required for manufacturing process p (25):

$$\sum_{r\in R}\sum_{p\in P} pra_{frpct}\cdot BoM_{pm} = \sum_{s\in S}\sum_{l\in L} tas_{sflmct} \qquad \forall f\in F, m\in M, c\in C, t\in T \tag{25}$$

Capacity and budget constraints

Inequation (26) defines production capacities of suppliers per period. We thus assume a homogenous demand from suppliers' customers.

$$CapS_{smt} \geq \sum_{\mathrm{f}\in \mathrm{F}}\sum_{\mathrm{l}\in \mathrm{L}}\sum_{c\in C} tas_{sflmct} \qquad \forall s\in S, m\in M, t\in T \tag{26}$$

Inequation (27) makes sure that resources are not overused. As we define this constraint per period, we assume that capacity usage is rather constant in time.

$$CapR_{frt} \geq \sum_{p\in P}\sum_{c\in C} pra_{frpct}\cdot CapReq_{frpct} \qquad \forall f\in F, r\in R, t\in T \tag{27}$$

Investments per period can be restricted using inequation (28):

$$MaxCapEx_{t} \geq \sum_{a\in A}\frac{capEx_{at}}{ERH_{at}} \qquad \forall t\in T \tag{28}$$

Binary Variables

Inequations (29) and (30) guarantee that binary variable x_{ft} only takes the value 1, if the production amount in a certain facility pra_{frpct} is larger than zero.

$$\sum_{\mathrm{r}\in R}\sum_{p\in P}\sum_{c\in C} pra_{frpct} \leq BigM\cdot x_{ft} \qquad \forall f\in F, t\in T \tag{29}$$

$$x_{ft} \leq \sum_{\mathrm{r}\in R}\sum_{p\in P}\sum_{c\in C} pra_{frpct} \qquad \forall f\in F, t\in T \tag{30}$$

Binary variable y_{frt} only takes the value 1, if a certain resource r is used at time t.

$$\sum_{\mathrm{p}\in P}\sum_{c\in C} pra_{frpct} \leq BigM\cdot y_{frt} \qquad \forall f\in F, r\in R, t\in T \tag{31}$$

$$y_{frt} \leq \sum_{p\in P}\sum_{c\in C} pra_{frpct} \qquad \forall f\in F, r\in R, t\in T \tag{32}$$

Duties

Usually, material flows are not exactly modeled in linear supply chain design models (ARNTZEN ET AL., 1995, p. 76). However, we have to model the material flows in detail in order to calculate duties and delivery times. In order to define the relevant constraint we assume that:

- Each bill of materials is convergent.
- A certain material or semi-finished product is supplied by a single supplier for each final customer of each product.
- Each semi-finished product for a certain customer is manufactured by one facility only.

Equation (33) makes sure that only one supplier delivers materials for a certain product and a certain customer:

$$\frac{tas_{sflmct}}{\left(\sum_{p \in P} BoM_{mp}\right) \cdot Dem_{cxt}} = tas_{sflmct}^{(0;1)} \qquad (33)$$
$$\forall s \in S, f \in F, l \in L, m \in M, c \in C, t \in T, x \in X_m, Dem_{cxt} \neq 0$$

Constraints (34) and (35) guarantee that for each product-customer combination only one facility is used:

$$\frac{tai_{fglpct}}{Dem_{cxt}} = tai_{fglpct}^{(0;1)} \qquad (34)$$
$$\forall f \in F, g \in F, l \in L, p \in P, c \in C, t \in T, x \in X_p, Dem_{cxt} \neq 0$$

$$\frac{tac_{fclxt}}{Dem_{cxt}} = tac_{fclxt}^{(0;1)} \qquad (35)$$
$$\forall f \in F, c \in C, l \in L, x \in X, t \in T, Dem_{cxt} \neq 0$$

Duties and Duty Drawbacks regarding material flows

Duty values larger than zero are calculated, if a supplier s delivers to a facility f and if f and c are located in the same country b, while s is located in another country a. The duty values are calculated by multiplying the material price by the delivered amount of materials, while exchange rates have to be taken into account (right side of first row in (36)).

Furthermore, it has to be taken into account that duty value is zero for semi-finished products that are exported from the receiving facility to any other country for further manufacturing steps. Note, that the duty value is non-negative as defined by (49).

$$\begin{aligned}
& dutyValueM_{mabct} \geq \sum_{s \in S_a} \sum_{f \in F_b} \sum_{l \in L} tas_{sflmct} \cdot PrM_{smt} \cdot ER_{abt} \\
& - \sum_{\substack{f \in F \\ f \notin F_b}} \sum_{g \in F_b} \sum_{l \in L} \sum_{p \in P_m} tai_{fglpct} \cdot BigM - \sum_{\substack{f \in F \\ f \notin F_b}} \sum_{l \in L} \sum_{x \in X_m} tac_{fclxt} \cdot BigM \\
& \forall \; m \in M, a \in A, b \in A \text{ and } a \neq b, c \in C_b, t \in T
\end{aligned} \tag{36}$$

Duties and Duty Drawbacks regarding semi-finished products

Duty values larger than zero for semi-finished products p result, if company's facility f in country a delivers to another facility g in a different country b, where customer c is located as well. The duty value results from multiplying the imported amount of semi-finished products by the transfer price. The latter is defined in the home currency of company headquarters, so that it might have to be transferred into the currency of the receiving company unit or firm (first row, right side of (37)).

In case the semi-finished product comprises materials or other semi-finished products that have been manufactured in the customer's home country, the money value of these elements can be deducted from the duty value (second row of (37)). Duty values are zero, if products resulting from consecutive production steps are imported into the customer's home country (row 3 in (37)). Note, that $\mathrm{dutyValueP}_{\mathrm{pabct}}$ is non-negative (50).

$$
\begin{aligned}
& dutyValueP_{pabct} \geq \sum_{f \in F_a} \sum_{g \in F_b} \sum_{l \in L} tai_{fglpct} \cdot TP_{pt} \cdot ERH_{bt} \\
& - \sum_{s \in S_b} \sum_{f \in F} \sum_{l \in L} \sum_{m \in M_p} tas_{sflmct} \cdot PrM_{smt} - \sum_{f \in F_b} \sum_{g \in F} \sum_{l \in L} \sum_{q \in AscP_p} tai_{fglqct} \cdot PVC_{qt} \cdot ERH_{bt} \\
& - \sum_{\substack{f \in F \\ f \notin F_b}} \sum_{g \in F_b} \sum_{l \in L} \sum_{q \in DescP_p} tai_{fglqct} \cdot BigM - \sum_{\substack{f \in F \\ f \notin F_b}} \sum_{l \in L} \sum_{x \in X_P} tac_{fclxt} \cdot BigM \\
& \forall\, p \in P, a \in A, b \in A \,\text{mit}\, a \neq b, c \in C_b, t \in T
\end{aligned}
\tag{37}
$$

Duties and Duty Drawbacks regarding finished products

Inequation (38) calculates duty values regarding finished products. Since the facility that exports its products has to pay the duties, duty value is given in the currency of the country where this facility is located. Calculation is basically according to that for semi-finished products and the duty value is non-negative (51).

$$
\begin{aligned}
& dutyValueX_{xabct} \geq \sum_{f \in F_a} \sum_{l \in L} tac_{fclxt} \cdot \frac{PrX_{cxt}}{ER_{abt}} \\
& - \sum_{s \in S_b} \sum_{f \in F} \sum_{l \in L} \sum_{m \in M_x} tas_{sflmct} \cdot \frac{PrM_{smt}}{ER_{abt}} - \sum_{h \in F_b} \sum_{g \in F} \sum_{l \in L} \sum_{q \in P_x} tai_{hglqct} \cdot PVC_{qt} \cdot ERH_{at} \\
& \forall\, x \in X, a \in A, b \in A \,\text{and}\, a \neq b, c \in C_b, t \in T
\end{aligned}
\tag{38}
$$

Local (Domestic) Content Rules

Local Content LC_{at} is defined as a share of turnover has to be less than or equal to the cost for local supplies plus local value add as defined in (39):

$$
\begin{aligned}
& \sum_{f \in F} \sum_{c \in C_a} \sum_{l \in L} \sum_{x \in X} LC_{at} \cdot PrX_{cxt} \cdot tac_{fclxt} \leq \\
& \sum_{s \in S_a} \sum_{f \in F} \sum_{l \in L} \sum_{m \in M} \sum_{c \in C_a} tas_{sflmct} \left(\Pr M_{smt} + DistSF_{sf} \cdot CT_{lt} \cdot ERH_{at} \cdot WM_m \right) \\
& + \sum_{f \in F_a} \sum_{r \in R} \sum_{p \in P} \sum_{c \in C_a} pra_{frpct} \cdot PC_{frpt} \\
& + \sum_{f \in F_a} \sum_{g \in F_a} \sum_{l \in L} \sum_{p \in P} \sum_{c \in C_a} tai_{fglpct} \cdot DistFF_{fg} \cdot CT_{lt} \cdot ERH_{at} \cdot WP_p \\
& + \sum_{f \in F_a} \sum_{c \in C_a} \sum_{l \in L} \sum_{x \in X} tac_{fclxt} \cdot DistFC_{fc} \cdot CT_{lt} \cdot ERH_{at} \cdot WX_x \\
& + \sum_{f \in F_a} FixCF_{ft} \cdot x_{ft} + \sum_{f \in F_a} \sum_{r \in R} FixCR_{frt} \cdot y_{frt} \\
& \forall\, a \in A, t \in T
\end{aligned}
\tag{39}
$$

Determining Cycle Time

In order to calculate cycle time the Order Penetration Point has to be taken into account. We assume a Purchase-and-Make-to-Order principle, thus calculating cycle time beginning with the date of customer‘s order. This implies that no materials or semi-finished goods are kept in stock that are not assigned to a specific customer order. All times calculate to determine cycle time are average times that are set by the decision maker as parameters.

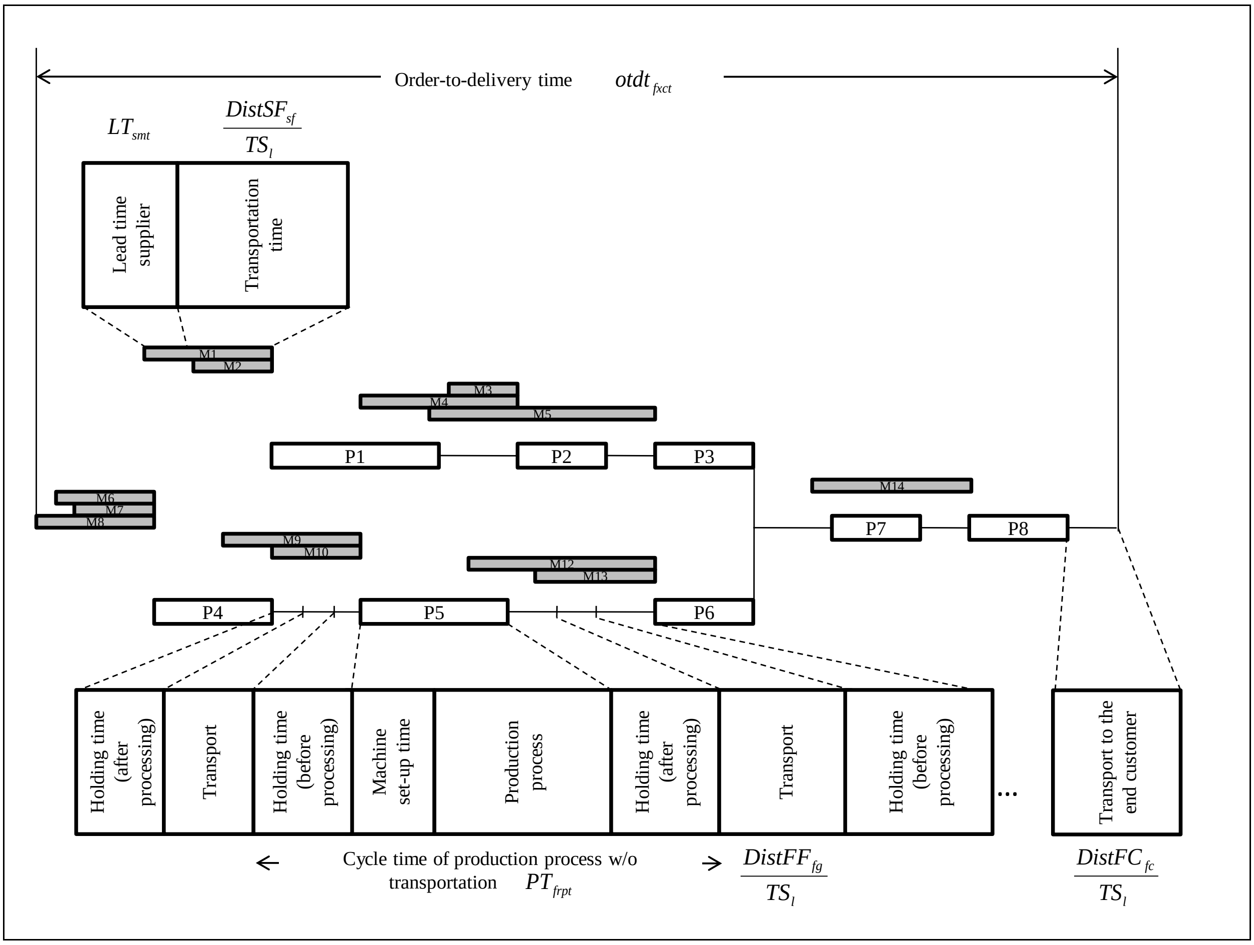

Figure 2: **Determining Cycle Time**

In a first step we look at all initial production processes. lt_{fpct} is non-negative (see (52)) and helps to define the points in time when successive manufacturing processes can be started.

$$lt_{fpct} - PT_{frpt} \cdot \frac{pra_{frpct}}{Dem_{cxt}} - \sum_{l \in L} \left(LT_{smt} + \frac{DistSF_{sf}}{TS_l} \right) \cdot tas_{sflmct}^{(0,1)} + M_1 \cdot \sum_{q \in P} BoP_{qp} \geq 0 \qquad (40)$$

$$\forall\ f \in F, r \in R, p \in P, c \in C, t \in T, s \in S, x \in X_p, m \in M \text{ and } BoM_{mp} \neq 0, Dem_{cxt} \neq 0$$

Inequation (41) defines the time until the first manufacturing step is accomplished in case no external supplies are needed to start production.

$$lt_{fpct} - PT_{frpt} \cdot \frac{pra_{frpct}}{Dem_{cxt}} + M_1 \cdot \sum_{q \in P} BoP_{qp} \geq 0 \qquad (41)$$
$$\forall\ f \in F, r \in R, p \in P, c \in C, t \in T, x \in X_p, Dem_{cxt} \neq 0$$

Inequation (42) takes a recursive approach to calculate the times after which all subsequent production processes are finished.

$$lt_{gpct} - PT_{grpt} \cdot \frac{pra_{grpct}}{Dem_{cxt}} - \sum_{l \in L} \frac{DistFF_{fg}}{TS_l} \cdot tai^{(0;1)}_{fglqct} - lt_{fqct} + M_1 \cdot \left(1 - \sum_{l \in L} tai^{(0;1)}_{fglqct} \right) \geq 0 \qquad (42)$$
$$\forall\ g \in F, r \in R, p \in P, c \in C, t \in T, x \in X_p, f \in F, p \in P \text{ und } BoP_{qp} = 1, Dem_{cxt} \neq 0$$

In case delivery time for needed materials is longer than the cumulated production time of preceding manufacturing steps, inequation (43) helps to consider this situation.

$$lt_{fpct} - PT_{frpt} \cdot \frac{pra_{frpct}}{Dem_{cxt}} - \sum_{l \in L} \left(LT_{smt} + \frac{DistSF_{sf}}{TS_l} \right) \cdot tas^{(0;1)}_{sflmct} + M_1 \cdot \left(1 - \sum_{l \in L} tas^{(0;1)}_{sflmct} \right) \geq 0 \qquad (43)$$
$$\forall \qquad f \in F, r \in R, p \in P, c \in C, t \in T, x \in X_p, s \in S, m \in M \text{ and } BoM_{mp} \neq 0, Dem_{cxt} \neq 0$$

Overall cycle time can be restricted to predefined value $MAXotdt$ as inequation (44) shows.

$$MAXotdt \geq \sum_{l \in L} \frac{DistFC_{fc}}{TS_l} \cdot tac^{(0;1)}_{fclxt} + lt_{fpct} \qquad (44)$$
$$\forall\ f \in F, c \in C, x \in X, p \in EP_x, t \in T$$

Emission Constraints

Emissions can be restricted to a pre-defined value $MaxEmPro_{cxt}$ for each customer, product and period as defined in (45). We calculate emissions due to the production process at the supplier’s site for needed materials and for transporting the materials to the company’s facility regarding the upstream supply chain. Regarding the internal supply chain we consider emissions due to the production process at the company’s facility and during transports between production sites. Regarding the downstream delivery chain we calculate emissions due to transports to the customers.

$$
\begin{aligned}
MaxEmPro_{cxt} \geq {} & \sum_{s}\sum_{f}\sum_{l}\sum_{m\in M_x} tas_{sflmct}\cdot\frac{EmM_{sm}}{Dem_{cxt}} + \sum_{s}\sum_{f}\sum_{l}\sum_{m\in M_x} tas_{sflmct}\cdot EmTM_{lm}\cdot\frac{DistSF_{sf}}{Dem_{cxt}} \\
& + \sum_{f}\sum_{g}\sum_{l}\sum_{p\in P_x} tai_{fglpct}\cdot EmTP_{lp}\cdot\frac{DistFF_{fg}}{Dem_{cxt}} + \sum_{f}\sum_{r}\sum_{p\in P_x} pra_{frpct}\cdot\frac{EmP_{rp}}{Dem_{cxt}} \\
& + \sum_{f}\sum_{l} tac_{fclxt}\cdot\frac{DistFC_{fc}\cdot EmTX_{lx}}{Dem_{cxt}} \\
& \forall\, c, x, t
\end{aligned}
\tag{45}
$$

Due to legal regulations emissions might be restricted for each production site (46):

$$
\begin{aligned}
MaxEmF_{ft} \geq {} & \sum_{r}\sum_{p}\sum_{c} pra_{frpct}\cdot EmP_{rp} \\
& \forall\, f, t
\end{aligned}
\tag{46}
$$

Non-negativity constraints and binary variables

$$investF_{ft} \geq 0 \qquad \forall\, f\in F, t\in T \tag{47}$$

$$investR_{frt} \geq 0 \qquad \forall\, f\in F, r\in R, t\in T \tag{48}$$

$$dutyValueM_{mabct} \geq 0 \qquad \forall\, m\in M, a\in A, b\in A, c\in C, t\in T \tag{49}$$

$$dutyValueP_{pabct} \geq 0 \qquad \forall\, p\in P, a\in A, b\in A, c\in C, t\in T \tag{50}$$

$$dutyValueX_{xabct} \geq 0 \qquad \forall\, x\in X, a\in A, b\in A, c\in C, t\in T \tag{51}$$

$$lt_{fpct} \geq 0 \qquad \forall\, f\in F, p\in P, c\in C, t\in T \tag{52}$$

$$pra_{frpct} \geq 0 \qquad \forall\, f\in F, r\in R, p\in P, c\in C, t\in T \tag{53}$$

$$tac_{fclxt} \geq 0 \qquad \forall\, f\in F, c\in C, l\in L, x\in X, t\in T \tag{54}$$

$$tai_{fglpct} \geq 0 \qquad \forall\, f\in F, g\in F, l\in L, p\in P, c\in C, t\in T \tag{55}$$

$$tas_{sflmct} \geq 0 \qquad \forall\; s\in S, f\in F, l\in L, m\in M, c\in C, t\in T \tag{56}$$

$$tvf_{f} \geq 0 \qquad \forall\, f\in F \tag{57}$$

$$tvr_{fr} \geq 0 \qquad \forall\, f\in F, r\in R \tag{58}$$

$$closeF_{ft} \in [0;1] \qquad \forall\, f\in F, t\in T \tag{59}$$

$$closeR_{frt} \in [0;1] \qquad \forall\, f\in F, r\in R, t\in T \tag{60}$$

$$tac^{(0;1)}_{fclxt} \in [0;1] \qquad \forall\, f\in F, c\in C, l\in L, x\in X, t\in T \tag{61}$$

$$tai^{(0;1)}_{fglpct} \in [0;1] \qquad \forall\, f\in F, g\in F, l\in L, p\in P, c\in C, t\in T \tag{62}$$

$$tas^{(0;1)}_{sflmct} \in [0;1] \qquad \forall\; s\in S, f\in F, l\in L, m\in M, c\in C, t\in T \tag{63}$$

$$x_{ft} \in [0;1] \qquad \forall\, f\in F, t\in T \tag{64}$$

$$y_{frt} \in [0;1] \qquad \forall\, f\in F, r\in R, t\in T \tag{65}$$

4.3 Multi-objective optimization

The ε-constraint method (HAIMES ET AL., 1971) is solving multi-objective optimization problems by transforming them into single-objective problems where all objectives but one are handled as constraints. Thus, the ε-constraint method is rather simple to apply. However, it does not generate a set of non-dominated solutions (Pareto frontier) in a single run.

Regarding our model the free cash flow to the firm should be maximized while both order-to-delivery-time and carbon footprint should be minimized simultaneously. In a first step free cash flow to the firm is maximized while setting no constraints regarding cycle time and carbon footprint. After that, both maximum allowed cycletime as well as maximum allowed carbon footprint are decreased incrementally starting at the values of the initial solution. While doing so, free cash flow to the firm will decrease step-by-step and a Pareto-optimal frontier is generated. Visualizing the Pareto-optimal decision alternatives might help the decision maker to assess the structure of the supply chain that meets his priorities regarding the different objectives the best.

5. CRITICAL REFLECTION AND SUMMARY

The model we presented focuses financial, ecological, and time measures simultaneously. By presenting a set of Pareto-optimal solutions, the decision maker is able to pick the preferred solution regarding all three objectives. When we applied the model in a real-life case study it proofed to be very helpful to manage the input parameters by using a computer-based tool that acts as an interface to the optimization program itself. Moreover, the results generated by the optimization tool should be handled by such a tool in order to facilitate adequate reporting and analysis, e.g. sensitivity analysis, of the data.

One of the most critical problems in real-life applications is retrieving the input data. Modeling large networks could result in a huge amount of input data, which is a problem in itself. Furthermore, many companies might not have the transparency needed to determine reliable parameter values. Thus, a certain - sometimes a rather large - degree of aggregation is indispensible when modeling global supply chains. As any multi-period planning model our approach requires forecasting of input data for a time horizon that could cover several years in our case.

Regarding the optimization procedure we apply it might be worthwhile to test genetic algorithms in order to be able to determine the Pareto frontier in a single run.

Many aspects that might be of interest for the decision maker have been neglected or simplified in our approach. Therefore, the model might have to be extended regarding:

- Variable material prices, including rebates.
- Learning effects in manufacturing.
- Variable production resources/constraints, including overtime work, additional shifts.
- Demand might not have to be fully satisfied, or stock could be build up from period to period.
- Regarding ecological objectives we focused on carbon footprint. However this is due to the intense discussion today in the media. Any other type of emission can be constrained or set as an additional objective. Emissions might have to be constrained according to the number of emission certificates the company owns or is ready to buy. This results in a decision problem that might have to be integrated in the supply chain design model. Furthermore, recycling activities and reverse supply chains might of be concern.
- Regarding local (domestic) content rules we assumed that a predefined quota has to be met. It might be interesting to check if higher import taxes or other fines might be more favorable than meeting the local content restrictions.
- We set transfer prices as input parameters. However, these prices might be optimization variables themselves, since they could significantly influence the profit situation of the company. However, manipulating transfer prices has to be according to the law of the countries involved.

- Cycle time has been calculated according to the Purchase-and-Make-to-Order principle. This would have to be altered for make-to-stock and other manufacturing types.

Notations

Indices:

$a, b \in A$	Set of countries
$AscP_p$	Set of ascendant processes of process p
$c \in C$	Set of customers
C_a	Set of customers located in country a
$DescP_p$	Set of descendant processes going directly or indirectly into process p
EP	Set of processes which are the final processes to complete a final product (end processes)
EP_x	Set of final processes to complete final product x
$f, g, h \in F$	Set of facilities (production sites)
F_a	Set of facilities located in country a
$l \in L$	Set of logistics modes
$m \in M$	Set of materials bought by suppliers
M_p	Set of materials needed directly or indirectly for production process p
M_x	Set of materials needed directly or indirectly for final product x
$p, q \in P$	Set of processes / semi-finished products
P_m	Set of processes / semi-finished products containing directly or indirectly material m
P_x	Set of processes / semi-finished products containing directly or indirectly final product x
$r \in R$	Set of resources
$s \in S$	Set of suppliers
S_a	Set of suppliers located in country a
$t \in T$	Set of time periods
$x \in X$	Set of final products
X_m	Set of final products x containing directly or indirectly material m
X_p	Set of final products x containing directly or indirectly semi-finished product p

Parameters:

$BigM$	A big positive number
BoM_{mp}	Direct demand of material m to produce semi-finished product p [u/m] (bill of materials)
BoP_{qp}	Direct demand of semi-finished product q to produce semi-finished product p [u/m] (bill of processes)
$CapR_{frt}$	Capacity of resource r at facility f in period t [time unit] (capacity of facility)
$CapReq_{frpt}$	Required capacity to produce p with resource r at facility f in period t [time unit / u/m]
$CapS_{smt}$	Capacity of supplier s to produce material m in period t [u/m]
CCF_{ft}	Saldo of ingoing and outgoing payments (cash flow) to close facility f in period t [monetary unit of f]

CCR_{frt}	Saldo of ingoing and outgoing payments (cash flow) to close ressource r at facility f in period t [monetary unit of f]
CT_l	Transport cost rate for logistics mode l [home monetary unit/kg*km]
Dem_{cxt}	Demand of customer c of finished product x in period t [u/m]
$DepF_f$	Depreciation of facility f [monetary unit of f]
$DepR_{fr}$	Depreciation of resource r at facility f [monetary unit of f]
$DistFC_{fc}$	Distance from facility f to customer c [km]
$DistFF_{fg}$	Distance from facility f to facility g [km]
$DistSF_{sf}$	Distance from supplier s to facility f [km]
$DutyRateM_{mabt}$	Duty rate in period t to import material m from country a to country b
$DutyRateP_{pabt}$	Duty rate in period t to import semi-finished product p from country a to country b
$DutyRateX_{xabt}$	Duty rate in period t to import finished product x from country a to country b
EmM_{sm}	Amount of CO_2 emitted to produce material m at supplier s
$EmTM_{lm}$	Amount of CO_2 emitted to transport material m with logistics mode l one kilometer
EmP_{rp}	Amount of CO_2 emitted to produce semi-finished product p with resource r
$EmTP_{lp}$	Amount of CO_2 emitted to transport semi-finished product p with logistics mode l one kilometer
$EmTX_{lx}$	Amount of CO_2 emitted to transport finished product x with logistics mode l one kilometer
ER_{abt}	Average exchange rate in period t for one monetary unit of country a a to currency of country b
$ER_{ab(c)t}$	Average exchange rate in period t for one monetary unit of country a a to currency of country b where customer c is located
$ER_{ab(s)t}$	Average exchange rate in period t for one monetary unit of country a a to currency of country b where supplier s is located
ERH_{at}	Average exchange rate in period t for one monetary unit of the home currency into the currency of country a
$FixCF_{ft}$	Fixed costs for facility f in period t [monetary unit of f]
$FixCR_{frt}$	Fixed costs for resource r at facility f in period t [monetary unit of f]
$InvCC_t$	Inventory carrying costs rate in period t
$InvF_{ft}$	Cash flow to open facility f in period t [monetary unit of f]
$InvR_{frt}$	Cash flow to open resource r at facility f in period t [monetary unit of f]
IVF_f	Value of facility f at $t = 0$ [monetary unit of f]
IVR_{fr}	Value of a resource r at facility f at $t = 0$ [monetary unit of f]
LC_{at}	Local content rate required in country a at period t
LT_{smt}	Lead time for material m of supplier s in period t [time units]
M_1	A big positive number

$MaxCapEx_t$	Maximum invest in period t [monetary unit of home currency]
$MAXotdt$	Maximum order to delivery time [time units]
$MaxEmPro_{cxt}$	Maximum amount of CO_2 to emit in period t in order to produce finished product x for customer c
$MaxEmPro_{cxt}$	Maximum amount of CO_2 allowed to emit in period t by facility f
PC_{frpt}	Variable production costs producing process p at resource r and facility f, in period t [monetary unit of f]
PrM_{smt}	Price in period t for material m at supplier s [monetary unit of s]
PrX_{cxt}	Sales price of finished product x in period t for customer c [monetary unit of c]
PT_{frp}	Average cycle time of production process p at facility f and resource r [time units]
PVC_{pt}	Value of process p accepted by customs) [monetary unit of home currency]
Tax_{at}	Average tax rates on profits in country a and t
TP_{pt}	Transfer price for intercompany deliveries of semi-finished product p in period t [monetary unit of home currency]
TS_l	Transport speed in logistics mode l [time units/km]
$WACC$	Weighted average cost of capital
WM_m	Weight of material m [kg]
WP_p	Weight of semi-finishes product p [kg]
WX_x	Weight of finished product x [kg]
X_f^{ini}	1, if facility f is open at $t = 0$, else 0
Y_{fr}^{ini}	1, if resource r at facility f is operated at $t = 0$, else 0

Decision Variables:

$capEx_{at}$	Aggregated Cash Flow resulting from investment activities in country a and period t [monetary unit of a]
$closeC_{at}$	Aggregated cash flow resulting from closing facilities and resources in country a and period t [monetary unit of a]
$closeF_{ft}$	1, if facility f is closed in period t, else 0
$closeR_{frt}$	1, if resource r at facility f is closed in period t, else 0
dep_{at}	Aggregated depreciations in country a and period t [monetary unit of a]
$dutyValueM_{mabct}$	Tariff value in period t for importing material m, that is needed for a product of customer c, from country a to country b [monetary unit of b]
$dutyValueP_{pabct}$	Tariff value in period t for importing semi-finished product p, that is needed for a product of customer c, from country a to country b [monetary unit of b]
$dutyValueX_{xabct}$	Tariff value in period t for importing finished product x for customer c, from country a to country b [monetary unit of b]
$ebitda_{at}$	Earnings before interest, tax, depreciation and amortization in country a and period t [monetary unit of a]
$fcff_{at}$	Free Cash Flow to the Firm in country a and period t [monetary unit of a]

$inventCC_{at}$	inventory carrying costs in country a and in period t [monetary unit of a]
$investF_{ft}$	Cash flow resulting from investment activities in facility f in period t [monetary unit of f]
$investR_{frt}$	Cash flow resulting from investment activities in resource r at facility f in period t [monetary unit of f]
lt_{fpct}	Lead time till finishing semi-finished product p at facility f that is needed for a product for customer c in period t [time units]
$otdt_{fxct}$	Order to delivery time in period t for a finished product x delivered by facility f for customer c [time units]
pra_{frpct}	Production amount in period t of semi finished product p needed for a product for customer c at facility f and resource r [u/m]
$pra_{frpct}^{(0;1)}$	1, if $pra_{frpct} > 0$, else 0
tac_{fclxt}	Transport amount in period t of finished product x from facility f to customer c using logistics mode l [u/m]
$tac_{fclxt}^{(0;1)}$	1, if $tac_{fclxt} > 0$, else 0
tas_{sflmct}	Transport amount in period t of material m needed for a product for customer c from supplier s to facility f using logistics mode l [u/m]
$tas_{sflmct}^{(0;1)}$	1, if $tas_{sflmct} > 0$, else 0
tai_{fglpct}	Transport amount in period t of semi finished product p needed for a product for customer c from facility f to facility g using logistics mode l [u/m]
tai_{gflqct}	Transport amount in period t of semi finished product q needed for a product for customer c from facility g to facility f using logistics mode l [u/m]
tai_{hglqct}	Transport amount in period t of semi finished product q needed for a product for customer c from facility h to facility g using logistics mode l [u/m]
$tai_{fglpct}^{(0;1)}$	1, if $tai_{fglpct} > 0$, else 0
tv_{a}	Terminal values of all assets (facilities and resources) in country a [monetary unit of a]
tvf_{f}	Terminal value of facility f [monetary unit of f]
tvr_{fr}	Terminal value of resource r at facility f [monetary unit of f]
x_{ft}	1, if facility f is opened in period t
y_{frt}	1, if resource r at facility f is operated in period t, else 0

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