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Sustainability optimization for global supply chain decision-making

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Abstract

Modern enterprises of all sizes operate in global manufacturing networks and complex global supply chains. Because sustainability is now a major concern, global manufacturing enterprises must optimize their global supply chain over multiple objectives including sustainability. It is important for such enterprises to analyze their global supply chain across all the three pillars of sustainability (society, economy and environment) when making a distribution network decision. A cradle-to-gate approach is taken, which means this decision can depend on the manufacturing site, all its suppliers, raw material source and transportation right until the customer gate. In this article, a multi-objective optimization model is presented that provides a rigorous method to optimize over all the three pillars of sustainability using a cradle-to-gate approach.

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Keywords: Sustainability; Green supply chain; Multi-objective optimization; Decision making

1. Introduction

Nowadays, besides huge multinational companies, small and medium-sized enterprises (SME) also operate in globally distributed supply chain networks [9]. Individual steps of the manufacturing process are performed on globally distributed sites. Furthermore, by focusing on core competencies, the proportion of purchased parts has significantly increased [18]. The industrial sector, particularly, has several impacts on the environment due its large supply chain and auxiliary processes like transportation and packaging [21]. The design of global supply chain networks is of increasing importance for the competitiveness of companies in the global market but also a growing challenge for the management. Currently, teams of experts advise on strategic decisions and mostly intuitively make quasi-rational decisions that, by far, do not include all the correlations of the global manufacturing network and its environment [17]. Such decisions can be supported by approaches in the field of operations research that map cause-effect relationships in the supply chain through optimization after applying stringent rules. By applying supply chain network optimization problems, exclusive consideration of costs based on attractive factor advantages is unsuitable for sustainable supply chain planning. Rather, multiple objectives have to be integrated into the evaluation [9, 11]. Following this, sustainability is increasingly becoming an important objective for decision-making in global enterprises. Sustainability evaluation is sub-divided into three broad categories, namely environmental, social and economic sustainability - often referred to as the 'triple bottom line'. Environmental sustainability deals with the direct impact on the environment whereas economic sustainability refers to the involved costs and financial stability. Social sustainability, the least studied component of the three pillars of sustainability, deals with health, safety and livable conditions for people, communities, consumers and other stakeholders without compromising their rights or freedom. In order to fully understand and evaluate the sustainability of a production network or a global supply chain, a combined study of all these three branches of sustainability is required. It is not only significant to evaluate the sustainability of a supply chain, but also to optimize it over the three branches of sustainability and aid in supply chain decision-making.

2. State-of-the-art

The evaluation and optimization of sustainable

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manufacturing is becoming increasingly important. Several models have been developed over the recent years in order to estimate and understand the environmental impact of manufacturing processes, enterprises and their supply chains. Some of the approaches focus on the machinery and process level, others on process chains and factory level. A few approaches, such as [3,10], focus on global supply chains.

The planning of global supply chain networks is increasingly discussed taking into account environmental and social aspects. Reinhart [15] presents an approach for the holistic optimization of energy and resource consumption within supply chains. The approach focuses on the optimization of energy and resource efficiency at the three levels machinery, factory and supply chain. Energy and resource consumption are in the center of interest, based on the transport volume between the different factories.

Reich-Weiser et al. [14] developed a tool for supply chain optimization considering environmental sustainability based on energy payback time. Sarkis [16] developed decision-making frameworks for green supply chains which primarily pertained to environmental sustainability.

Metrics for social sustainability were developed by Hutchins and Sutherland [5] and a methodology for evaluating social sustainability in supply chains was proposed. A 31-subcategories system for social sustainability was published by the UNEP [12] which categorized each of the subcategories under stakeholders like community, worker, supplier and consumer. Standards like the ISO 26000 and the UN Global Compact have encouraged and enabled global enterprises to evaluate their Corporate Social Responsibility.

Few attempts have been made recently at evaluating the complete sustainability of a system including economic, environmental and social aspects. Erol et al [4] developed a fuzzy multi-criteria framework for sustainability evaluation, but an optimization technique cannot be coupled to this model to aid decision-making. Zhou et al [22] assessed the sustainability performance of continuous processes using a Goal Programming optimization model, but their study was limited to a single-stage manufacturing system.

The approaches of Chaabane [2], Naini [13], and Sundarakani [19] allow an assessment of supply chains in terms of their economic and environmental sustainability. Similar approaches described by Tseng [20] Abdalla [1] Jamshidi [7] and Zhou et al. [22] involve optimization models in which economic and environmental objectives were considered.

In summary, none of the presented approaches aid in decision making over the indicators of social, environmental and economic sustainability in combination with a modular optimization model to optimize the structure of a global supply chain. Therefore, the objective of the presented article is to formulate all the indicators to evaluate sustainability in global supply chains, derive a complete multi-objective optimization model for global supply chains and to find the optimal supply chain structure using the cradle-to-gate approach.

3. Measures for sustainability in global supply chains

The sustainability measures for optimization are developed separately for environmental sustainability in section 3.1 and social sustainability in section 3.2. Previous work on economic sustainability are discussed in section 3.3.

3.1. Environmental sustainability

Every component of the global supply chain has an impact on the environment. Since a cradle-to-gate approach is employed, the impacts from extraction of raw material right up to transportation of the final product to the customer gate is considered. The sub-measures are developed separately for the different components of the supply chain, namely, suppliers, sites, technologies and transport.

The sub-measures developed for the evaluation of environmental sustainability are summarized in Table 1 for a technology element as an example. The indicators in Table 1 are formulated for a typical machining process. The sub-measures for a single manufacturing process, referred to as a 'Technology Element' in the model, are developed based on an input-output diagram as shown in Figure 1. Similarly, Figures 2, 3 and 4 show the input-output diagrams for Supplier, Site and Transport elements respectively.

The indicators of all the environmental sustainability sub-measures are of different units, but due to the widespread use of Life-Cycle Analysis (LCA) techniques and inventory databases, each of these indicators can be converted into a common unit using an LCA software. For example, the total GWP (Global Warming Potential) of the entire supply chain can be evaluated from the environmental sustainability sub-measures and indicators by using a relevant LCA database.
The broad sub-measures for any technology element are identified as Energy, Consumables, Maintenance, Wastes and By-Products. Consumables for a technology element include water, coolant, oils, tooling, gauging and packaging material.

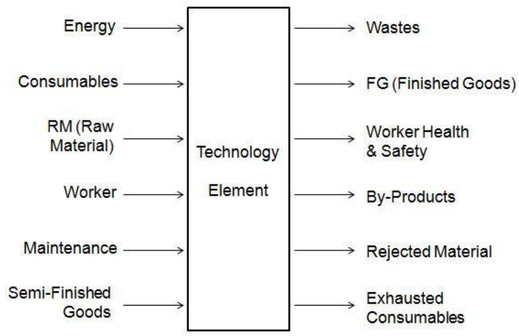

Fig. 1. Input-Output Diagram of a Technology Element.

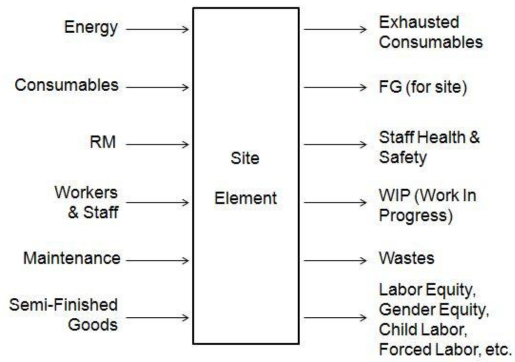

Fig. 2. Input-Output Diagram of a Site Element.

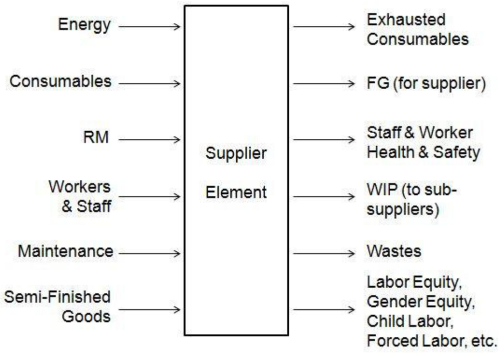

Fig. 3. Input-Output Diagram for a Supplier Element.

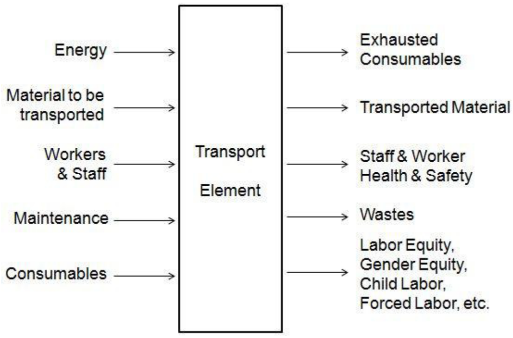

Fig. 4. Input-Output Diagram for a Transport Element.

Table 1. Environmental Sustainability Sub-measures and Indicators for a Technology Element.

Sub-measure	Indicator	Unit
Energy	Electricity consumption	kWh
	Fuel consumption	Liters
Consumables	Cutting oil	Liters
	Coolant	Liters
	Tooling	Kg
	Water	Liters
	Gauges	Kg
	Fixtures	Kg
	Packaging material	Kg
Maintenance	Water	Liters
	Detergent	Kg
	Spare parts replacement	Kg
	Grease	Liters
	Oil	Liters
By-products	Recycling	Kg
	Landfill	Kg
	Incineration	Kg
Wastes	Solid wastes	Kg
	Liquid wastes	Liters

3.2. Social sustainability

There are a large number of sub-measures for evaluating Social Sustainability, but the standard 31-category system published by the United Nations Environment Program is closely followed [12]. Based on the Input-Output Diagrams for the various components of the supply chain, social sustainability sub-measures and indicators are developed for each of these components for each category. These are presented in Table 2 for a site, which consists of multiple technology elements.

Freedom Of Association is assumed to be good for sustainable development, in line with the ILO report [6] - so the model aims at maximizing this indicator. Some qualitative indicators for social sustainability are considered in the binary form, since obtaining correct data and developing an indicator around it is infeasible in the real world.

In order to obtain quantitative evaluation techniques for a specific social sustainability measure like Access to Materials, the region-specific and enterprise-specific materials have to be looked at. In a broad sense, the sub-measure can be treated as a binary function, but can be made quantitative for a specific enterprise.

Table 2: Social Sustainability Sub-Measures and Indicators for a Site element.

Sub-measure	Indicator	Unit
Delocalization & migration	People resettled	Number
Community engagement	Volunteer hours	Hours
Cultural heritage	Is it preserved?	Binary
Indigenous rights	Is it preserved?	Binary
Access to material sources	Is it restricted?	Binary
Access to immaterial sources	Is it restricted?	Binary
Community security	Number of cases	Number
Public commitment	Do they hold promises?	Binary
Economic development	Revenue increase	$
Corruption prevention	Number of cases	Number
Technology development	Is it assisted?	Binary
Fair competition	Is it allowed?	Binary
Intellectual property rights	Are they preserved?	Binary
Supplier relationships	Supplier satisfaction	%
Social responsibility	Suppliers audited	%
Social security	Workers with paid time-off	%
Labor equity	Cases of discrimination	Number
Gender equity	Ratio of women employees	%
Child labor	Child labor ratio	%
Community safety	Cases of health effects	Number
Working hours	Amount of over-time work	Hours
Fair salary	Fair salary ratio	%
Freedom of association	Is it encouraged?	Binary
Forced labor	Forced labor ratio	%
Community service	Donation amount	$ / year
End of life responsibility	Incidents of non-compliance	Number
Local employment	Local employment ratio	%
Prevention of armed conflicts	Are resources which may lead to conflicts used?	Binary

3.3. Economic sustainability

Sub-measures for economic sustainability are developed for the technology, site, supplier and transport elements based on their input-output diagrams, by calculating the costs associated with each of the entities in those diagrams. A cost-based optimization using a similar optimization procedure has already been developed in previous work [8]. So, a multi-objective optimization problem is defined in Section 4 with environmental, social and economic sustainability as the objective functions.

4. Multi-objective optimization model for global multi-echelon supply chains

The objective of the present approach is to validate the effect of sustainability on decision making in the context of global supply chains. Thus, a multi-objective optimization model has been developed to optimize the structure of a global supply chain. The multi-objective optimization model is based on the model that has been presented in [8]. In addition, an objective function for sustainability measures has been generated and integrated into the model. Three target objectives, namely economic, social and environmental sustainability have been applied. In the following section, the optimization model with the existing solution method is briefly introduced and the objective functions for environmental and social sustainability are derived.

4.1. General supply chain network model and corresponding optimization model

To include all relevant objects within a supply chain, a network model focusing on objects such as material suppliers l and component suppliers z, manufacturing sites s, available technologies t, customers k and the transport modes v were set up previously. Also relevant is the manufacturing process with manufacturing steps w which can be performed by the technologies and the materials m which are necessary to operate the manufacturing process. Finally, the transport process t can be performed by the various transport modes v. Summing up, a configuration of the supply chain is described by the same decision variables as shown in [8].

The amount of objective functions is reduced to 3 objectives. For each of the objectives' cost, social sustainability and environmental sustainability, a linear objective function is developed. The function for costs was presented in [8], the sustainability functions are derived in 4.2 and 4.3. The basic functions are converted into one common unit in a mono-objective replacement problem by means of a transformation. As a common unit, the benefit is applied. For this purpose, the upper and lower limits for the objectives are defined. These allow the normalization of the target dimensions on the interval [0,1]. The result is a vector-valued objective function with:

$$\max \mathrm{u(Conf)} = \begin{pmatrix} \mathrm{u_{economic}} \\ \mathrm{u_{environment}} \\ \mathrm{u_{social}} \end{pmatrix} \quad (1)$$

This maximization problem can be solved by scalar methods. The presented approach uses the reference point to a distance method [23] which delivers the following objective function that has to be minimized:

$$\min_{\mathrm{u}} \sum_{\mathrm{i}=1}^{3} \lambda_{\mathrm{i}} \, |1 - \mathrm{u_i(Conf)}| \quad (2)$$

λi includes the individual weightings of the objectives related to the preferences of the deciders.

The constraints secure inter-linkages in the supply chain such as a consistent material flow within the supply chain network, or the fulfillment of capacity restrictions. The objective function has to be minimized under the constraints introduced in [8]. The resulting mixed-integer problem can be solved by various commercial solvers.

4.2. Environmental sustainability function

In this section, the formula for the evaluation of environmental sustainability in global supply chains is derived with the example of energy consumption. In terms of the energy consumption of a global supply chain, the overall network, from cradle to gate, meaning from materials, via manufacturing processes till the delivery to customers has to be included. Following this, the overall energy consumption consists of the energy consumption at the manufacturing of products on technologies (first term in equation 3), the general consumption of energy at sites, which is not directly related to a manufacturing process (term 2), consumption for material supply (term 3), the energy consumption for the manufacturing of components for component suppliers (term 4), the energy consumption of material transport between material suppliers and sites (term 5), the transport between component suppliers and sites (term 6) and the consumption for transport of semi finished components between sites (terms 7 and 8). For the energy consumption of the manufacturing processes, the consumption EM_{st} per hour per technology t at site s is multiplied with the amount of parts x_{pwst} and the manufacturing time PT_{pwst}. For the energy overhead, which is not directly linked with a manufacturing process, the yearly consumption of the plants EM_s is multiplied with the decision variable X_s, which ensures that energy is only added if the site is open. Energy consumption for material supply sums up all energy consumption per hour EM_l multiplied with manufacturing hours per materials LT_{lm} and amount of supplied materials t_{lspmv} per supplier. Similar logic applies to components which are supplied by component suppliers z in term 4. Additionally, energy consumption of transport as a sum of the energy consumption of the transport mode EM_v per km multiplied with distance $LSDist_{ls}$ between supplier l and the supplied sites s and the amount of supplied materials t_{lspmv} includes the energy consumption per supplied materials. Similar logic applies for terms 6 to 8.

$$E_{env} = \sum_{s=1}^{S} \sum_{t=1}^{T} \sum_{p=1}^{P} \sum_{w=1}^{W} EM_{st} \times PT_{pwst} \times x_{pwst} + \sum_{s=1}^{S} EM_s \times X_s + \sum_{l=1}^{L} \sum_{s=1}^{S} \sum_{p=1}^{P} \sum_{m=1}^{M} \sum_{v=1}^{V} EM_l \times LT_{lm} \times t_{lspmv} + \sum_{z=1}^{Z} \sum_{s=1}^{S} \sum_{p=1}^{P} \sum_{w=1}^{W} \sum_{v=1}^{V} EM_z \times ZT_{zw} \times t_{zspwv} + \sum_{v=1}^{V} \sum_{m=1}^{M} \sum_{p=1}^{P} \sum_{s=1}^{S} \sum_{l=1}^{L} EM_v \times LSDist_{ls} \times t_{lspmv} + \quad (3)$$

$\sum_{v=1}^{V}\sum_{w=1}^{W}\sum_{p=1}^{P}\sum_{s=1}^{S}\sum_{z=1}^{Z} EM_v \times ZSDist_{zs} \times t_{zspwv} + \sum_{p=1}^{V}\sum_{s_i=1}^{S}\sum_{w=1}^{W_p}\sum_{s_j=1}^{S}\sum_{v=1}^{V} EM_v \times SSDist_{s_i s_j} \times t_{s_i s_j pwv} + \sum_{v=1}^{V}\sum_{p=1}^{P}\sum_{s=1}^{S}\sum_{k=1}^{K} EM_v \times t_{skpv} \times KSDist_{ks}$

To include the environmental measure for sustainability within the optimization model, the measure has to be transformed into a benefit function $u_{environment}$ as described in section 4.1. For that reason, maximum and minimum allowable values $E_{environment}^{max}$ and $E_{environment}^{min}$ for energy consumption have to be defined. As the Energy consumption should be minimized, highest benefit $u_{environment}$ can be reached with the following linear transformation:

$$u_{environment} = \frac{E_{environment}^{max} - E_{environment}}{E_{environment}^{max} - E_{environment}^{min}} \quad (4)$$

4.3. Social sustainability function

As a measure for Social Sustainability, the indicator Health & Safety, which includes worker safety for technologies and community safety for sites, is developed as a linear metric. First, the Health & Safety values for each of the located technologies (see term 1 equation 5) and the Health & Safety evaluation per sites for the indirect areas (term 2) are integrated in the assessment. In addition, in terms 3 and 4, the worker Health & Safety for material and component suppliers are addressed. Depending on the amount of supplied materials and components, the Health & Safety value of each supplier is included. Analogously, in dependence of the transport quantities for material, components and product transports the Health & Safety per transport mode are integrated. Overall, for the Social Sustainability, an average Health & Safety indicator of the production network arises :

$$E_{social} = \frac{\sum_{s=1}^{S}\sum_{t=1}^{T}\sum_{p=1}^{P}\sum_{w=1}^{W} ES_{st} \times x_{pwst}}{\sum_{s=1}^{S}\sum_{t=1}^{T}\sum_{p=1}^{P}\sum_{w=1}^{W} x_{pwst}} + \frac{\sum_{s=1}^{S} E_S \times X_S}{\sum_{s=1}^{S} X_S} + \frac{\sum_{l=1}^{L}\sum_{s=1}^{S}\sum_{p=1}^{P}\sum_{m=1}^{M}\sum_{v=1}^{V} ES_l \times t_{lspmv}}{\sum_{l=1}^{L}\sum_{s=1}^{S}\sum_{p=1}^{P}\sum_{m=1}^{M}\sum_{v=1}^{V} t_{lspmv}} + \frac{\sum_{z=1}^{Z}\sum_{s=1}^{S}\sum_{p=1}^{P}\sum_{w=1}^{W}\sum_{v=1}^{V} ES_z \times t_{zspwv}}{\sum_{z=1}^{Z}\sum_{s=1}^{S}\sum_{p=1}^{P}\sum_{w=1}^{W}\sum_{v=1}^{V} t_{zspwv}} + \frac{\sum_{v=1}^{V}\sum_{m=1}^{M}\sum_{p=1}^{P}\sum_{s=1}^{S}\sum_{l=1}^{L} ES_v \times t_{lspmv}}{\sum_{v=1}^{V}\sum_{m=1}^{M}\sum_{p=1}^{P}\sum_{s=1}^{S}\sum_{l=1}^{L} t_{lspmv}} + \frac{\sum_{v=1}^{V}\sum_{w=1}^{W}\sum_{p=1}^{P}\sum_{s=1}^{S}\sum_{z=1}^{Z} ES_v \times t_{zspwv}}{\sum_{v=1}^{V}\sum_{w=1}^{W}\sum_{p=1}^{P}\sum_{s=1}^{S}\sum_{z=1}^{Z} t_{zspwv}} + \frac{\sum_{p=1}^{V}\sum_{s_i=1}^{S}\sum_{w=1}^{W_p}\sum_{s_j=1}^{S}\sum_{v=1}^{V} ES_v \times t_{s_i s_j pwv}}{\sum_{p=1}^{V}\sum_{s_i=1}^{S}\sum_{w=1}^{W_p}\sum_{s_j=1}^{S}\sum_{v=1}^{V} t_{s_i s_j pwv}} + \frac{\sum_{v=1}^{V}\sum_{p=1}^{P}\sum_{s=1}^{S}\sum_{k=1}^{K} ES_v \times t_{skpv}}{\sum_{v=1}^{V}\sum_{p=1}^{P}\sum_{s=1}^{S}\sum_{k=1}^{K} t_{skpv}} \quad (5)$$

Contrary to the target objective for environmental sustainability, the Health & Safety function is to be maximized in the production network. Since the evaluation of Health and Safety is already normalized to the interval [0,1], it needs no further transformation and the metric can be directly integrated as an objective function in the optimization model.

5. Case study

The multi-objective optimization model was tested in collaboration with a medium-sized enterprise and a pilot supply chain network for one product. The manufacturing process for the product in regard is defined in a total of 13 manufacturing steps (w). The final stage describes the outgoing goods and shipment of products to customers. The manufacturing process of single parts which is combined in step 1-5. The commissioning of parts is comprised of steps 6-8. Step 9 visualizes the assembly process while steps 10-12 conclude the testing process for the final check.

The manufacturing steps with linked technologies are currently located in China (C), Germany (G), Poland (P). Material suppliers are exclusively available in Europe, mainly in Germany. In addition to existing sites, possible sites are located in India (I), Russia (R), USA (U) and South Africa (S) and included in the assessment. There are four customers in regard, Customer Germany, Customer USA, Customer China and Customer India with an overall demand of about 2000 products per year, which is exceeding the actual capacity of the global supply chain network by far. Fig. 5 visualizes the Status Quo of the current supply chain configuration and possible alternatives for solution space.

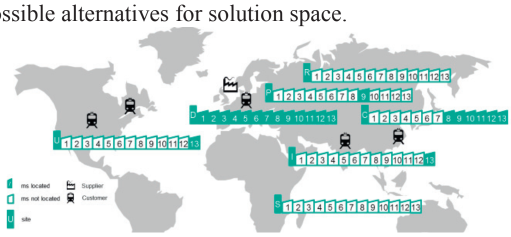

Fig. 5. Status Quo Supply Chain and solution space

The weightings of the objective criteria for the optimization model are assumed as follows: costs (33%), environmental sustainability (33%), social sustainability (33%). As constraints, strong local content requirements are fixed in the BRIC countries and USA. The plants in Russia and South Africa are of interest based on strategic considerations and tested within the optimization runs.

Based on the given solution space, an optimization run with IBM ® ILOG CPLEX solver has been performed and supply chain network configuration identified as followed in Fig. 6 :

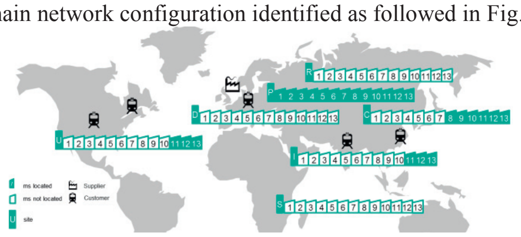

Fig. 6. Optimization result for sustainability

The optimization shows a clear preference to the site in Poland, where all the manufacturing steps for production of the product in regard are located. No manufacturing steps are located in Russia due to environmental and social impacts. In particular, the effects of environmental and social sustainability are so crucial, that cost effects no longer dominate the decision making towards the low-cost site in

Russia. In particular, energy consumption of the manufacturing processes as well as Health & Safety in Russia are much lower as compared to Poland, while costs are not significantly more. Furthermore, Germany, as a site, is closed as it is not preferred based on cost impacts. Sites in China, India and USA fulfill the local-content requirements, therefore manufacturing steps have to be located there.

6. Conclusion

This paper provides a technique of optimization of supply chain networks involving the three pillars of sustainability namely economic, environmental and social sustainability. It gives a broad overview about measures and indicators for the evaluation of the three pillars and links every indicator with an element of the supply chain network. The elements of the supply chain network are based on a multi-objective optimization model which has been adapted to include the three objective costs, namely economic, environmental and social sustainability. For the last two measures, new objectives functions were formalized and integrated into the optimization model. Additionally, the new optimization model for the evaluation and optimization of sustainability in supply chain networks was tested in collaboration with a medium-sized enterprise. To improve the optimization model and the interpretation of the findings, the integration of future developments for trends in energy prices will be studied. In fact, the uncertainty for developments has to be considered adequately. It is of great interest to identify the optimized network alternatives for costs, environmental sustainability and social sustainability separately and to discuss the advantages and disadvantages for the different supply chain configurations with deciders.

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