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Evaluating The Ecological Sustainability Of Production Networks – A Databased Approach

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Abstract

The design of global production networks influences the ecological sustainability of manufacturing operations, since it determines the environment with which a production process interacts. Historically sustainability has not been a primary goal for the design of production networks and its evaluation remains a challenge. The multiple goals of sustainability and complex structures of production networks constitute to a high modelling effort that can only be managed with databased solutions. To further decrease the modelling expenditures, the data used in such a solution should be already available or easy to obtain. This paper presents a methodology and data framework to evaluate various ecological sustainability goals, which are impacted by the design of global production networks. The approach is validated with a supplier for household appliance manufacturers.

Keywords

Ecological Sustainability; Global Production Networks; Data Framework; Modelling

1. Introduction

Global production networks (GPNs) are in a perfect storm at the start of the new decade [1]. In addition to the effects of digitalization and increasingly protectionist policies, the imperative of sustainability represents a new challenge for global manufacturing companies. GPNs are directly affected by the demands for greater sustainability, as the production network configuration of a GPN influences the ecological sustainability of value chains [2]. Nowadays, industrial value creation largely takes place in GPNs [3]. Therefore, the design of these networks influences what resources are used for production activities worldwide. Location-dependent factors that influence the environmental impact of a factory include national electricity mixes, regional water shortages, municipal recycling rates and local biodiversity. Further the manufacturing industry and associated transportation account for three-quarters of the global energy consumption [4]. Allocating manufacturing activities to green energy sites will mitigate the environmental impact of this energy consumption.

In the past established methods for designing GPNs merely considered criteria related to economic competitive advantages such as costs, flexibility, delivery capability and quality [5]. Therefore the associated evaluation models only included the system elements of GPN, but not their sustainability-relevant attributes. However most elements in a GPN have quantifiable properties that have a direct influence on sustainability targets, such as energy, water and material consumption or the generation of waste and emissions. For the evaluation of the ecological sustainability, information about these properties is absolutely necessary. In particular, the complexity of GPN, which include both a local product and process view as well as a global location view on different environmental conditions, poses a challenge. Therefore, there is a need for a methodology to assess the ecological sustainability of GPN [6]. Due to the size and complexity of such

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networks and the multidimensionality of ecological sustainability, the associated models must be data-based and scalable [7].

The added value of information gained through more detailed modelling should always be in proportion to the associated, increasing effort [8]. A driver of effort is that much of the required sustainability-related information is currently not collected in companies and must be gathered at a corresponding cost [9]. The background to this is that little use is made of the possibilities of digital data processing. Instead, data is transferred using Excel and similar manual interfaces, especially if the data requirements of the new model are not clearly defined and documented [10]. Production networks contain a large number of system elements, which cannot be completely taken into account for the modelling. The appropriate level of abstraction depends strongly on the respective task and the system under investigation, so that no uniform definition is possible [11]. Approaches that have a high level of aggregation cannot represent the exact mechanisms in the network [12]. On the other hand, approaches with a high level of detail have such a large information need that they are also not operational [13]. This creates the challenge that there is no uniform abstraction level for the scope of observation therefore it leads to the need to develop a data model that enables a flexible aggregation thanks to suitable syntax and semantics.

2. State of the art

In this context, research approaches regarding the ecological sustainability evaluation of production network design should be considered. The most current and relevant approaches are presented in the following.

The software tool "*OptiWo*" represents the core of the solution approach for data-based production network evaluation developed by SCHUH ET AL. [14]. The tool offers the possibility to model a production network according to a data model. The required data can be entered by the users and derived from the operational IT systems [15]. Required data sets for network modeling include location, machinery, process chain and transportation data [16]. The IT-based solution offers a clear data modeling and key figure calculation, which is partly combined with optimization approaches. However, due to the focus on cost calculation, the approach does not offer the possibility to map impact relationships in the context of ecological sustainability. The influencing factors and elements involved are partially modeled, but without attributes about the required information for the calculation of sustainability parameters. The work of MOURTZIS ET AL. includes a software solution consisting of various tools with the aim of determining the optimal design of product networks capable of manufacturing individual products according to customer requirements. The criteria taken into account are production and transport costs, lead time, quality, reliability, dynamic complexity, and the ecological indicators CO2 emissions and energy consumption [17]. Even though sustainability-related goals were considered, the aspects of water use, materials, waste and biodiversity are missing from the work.

The information model developed by CABRAL aims to measure the agility, resilience and environmental characteristics of a supply chain. The required key figures were developed on the basis of a literature research and validated by a Delphi survey of experts from science and industry [18]. However, the focus is more on supply chain management, i.e. operational control, and not on the long-term and strategic design of a production network. The approach of HELMIG serves to evaluate the use of sustainable logistics concepts in corporate networks. For this purpose, a system of key figures, a mapping of network elements and a structuring of logistics concepts were developed as descriptive elements. The sustainability-related indicators considered include energy consumption, packaging quantities, recycling rates, and noise. There is no consideration of a broader understanding of sustainability and a complete production network configuration [19].

The use of data from the operative supply chain control for the realization of life cycle assessments (LCA) represents the core idea of the work of PAPETTI ET AL. For the implementation of the method, a web tool was developed, which is used according to the developed procedure. Especially for the challenges of databases and structures as well as the derivation of quantities for the LCA, a detailed solution is described. Allocation decisions, on the other hand, are ignored and a reference is made to the standardized procedure of the LCA for the indicator calculation [20]. In the study by BORONOOS ET AL. a multi-objective mixed integer programming problem for the design of a closed-loop green supply chain network was developed. The proposed model aims at minimizing total costs, total CO2 emissions and robustness costs in forward and reverse direction of the material flow simultaneously. By integrating various political regulatory mechanisms, the approach offers a degree of novelty. At the same time, this led to the case that no further sustainability targets were integrated in addition to the quantity of emissions [21].

In summary, approaches to evaluate the sustainability of production operations and supply chains can be found in the literature. However, a detailed focus on the ecological sustainability of GPNs and their impact due to allocation decisions is lacking.

3. Conception of the approach

The approach should enable the evaluation of the ecological properties of a production network with as minimal effort as possible. For this purpose, the approach is divided into three parts: the data model, the information identification and the calculation of the evaluation results. The considered ecological sustainability aspects of this evaluation are based on the relevance analysis of SCHUH ET AL. [22]. The same applies to the data model, which is based on preliminary work by the same authors, due to its established benefits regarding operational performance [15]. The connection of the information needs of the data model with potential sources is derived out of a literature research on the different types of sources. The final calculation of evaluation parameters adapts the balancing idea in accounting. Since not all formulas can be presented in the scope of this publication, only an exemplary explanation takes place, which is extended in the application in section 4.

3.1 Data model for production network evaluation

The UML modelling standard is used to represent and document the structure of the data model. From this standard, the class diagram method is used to represent the objects and properties of a network as corresponding classes and attributes. The presented data model is based on the framework presented by SCHUH ET AL. and was extended to fit the data needs of a sustainability evaluation [14].

For a better overview and modular use, the model is divided into four levels. The four levels are the network, location, system and process levels. These levels are based on the established structural levels of a production network [23]. To ensure that the model functions properly and makes sense, the data structure and the accounting formulas were reviewed in semi-structured interviews and workshops with experts from industrial companies and adjusted as necessary. Figure 1 shows the complete data model with all classes and their associations. It can be seen that the individual levels and modules have internal relationships and defined interfaces to the outside. At the network level, the focus is particularly on the connections between the network nodes, i.e. the locations or production sites. Since only the configuration and not the coordination of the network is modelled, mainly transports and the associated objects are represented. An elementary class is therefore the transport route, which defines the logistical connection between two locations.

In the location layer, the nodes of the network, i.e. the different locations, are modelled. The sustainability properties of a production site are modelled both with the class attributes and via an assignment to profiles. Profiles are used to summarize the sustainability attributes of a particular category. In addition, multiple sites in close proximity can have the same profile, reducing modelling efforts. The energy profile indicates which energy types and emission factors are available to the site for the purchase of electricity, heat, cooling and steam. The circularity profile refers to the site-specific options for reusing materials in the sense of a circular economy.

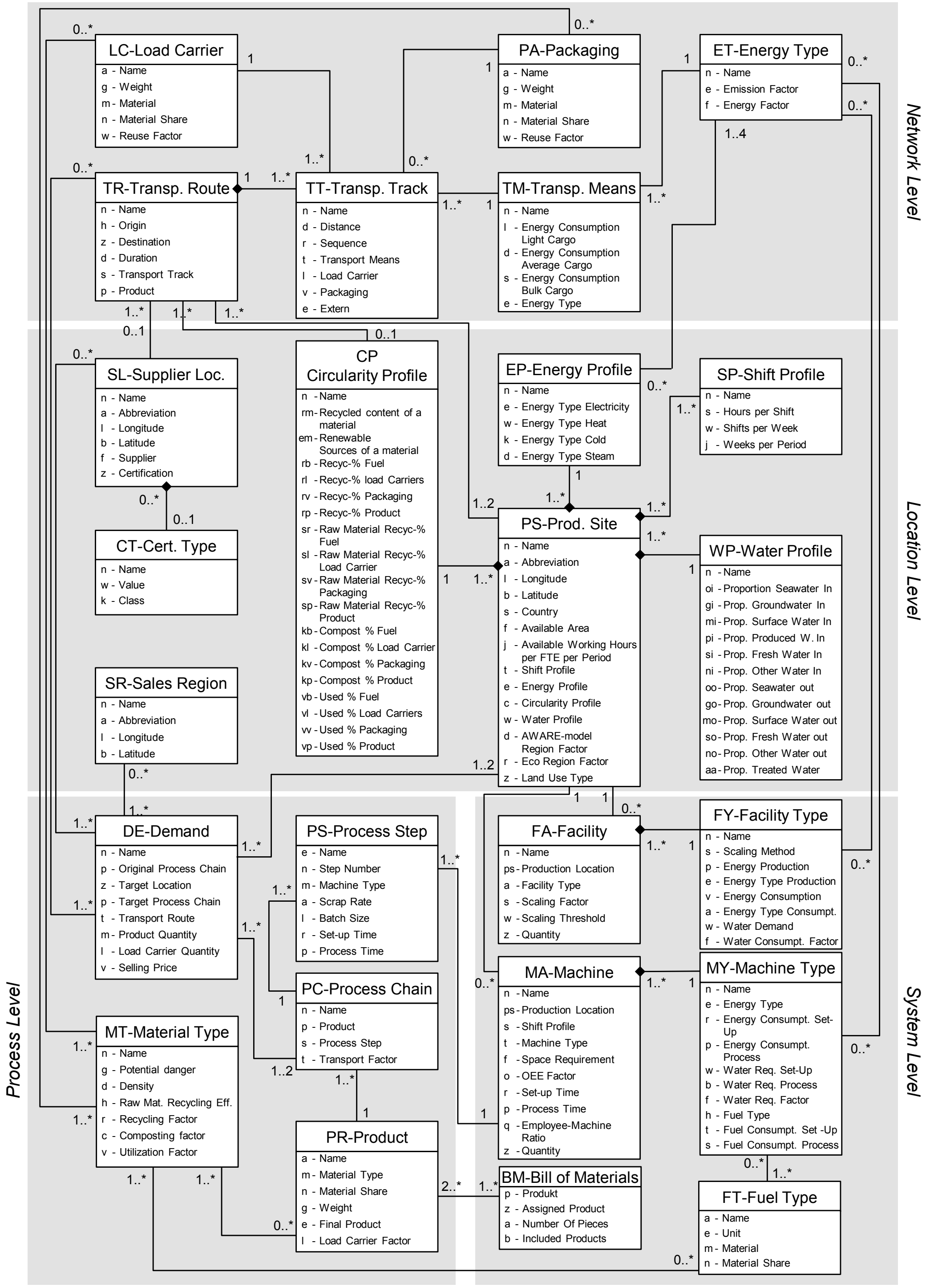

Figure 1: Data model for the ecological evaluation of production network configuration

The system level summarizes the production segments, systems and technologies allocated to a site. To keep the model manageable and at low-effort, only machines and facilities are explicitly named. Both are implemented in a scalable detail. For example, a machine can describe a single workstation or a complete production line. The difference between machines and facilities in this model lies in the proximity to the manufacturing process, which is also clear with the association assignment.

The process level maps which production processes take place in the network so that intermediate or end products are created. In addition to the closely linked products and production processes, the demand for these and the quantities per process are also an important component of this level. For a functioning model, it is necessary that the respective products and their production processes at one or more locations are allocated to the machines available there. For each of these allocations, the number of units of the products to be manufactured must also be defined. All this information is managed in the demand class. The attributes of these classes define which quantities flow from one process chain to the next and at which location both process chains are located. If these locations are different, a transport route must also be specified.

3.2 Identification of data sources for the data model

Structuring the information in a data model is merely the basis for modelling the ecological sustainability of production network configurations. In operational use, the procurement of the necessary data in particular is crucial for the success of a sustainability evaluation. As shown in Table 1, potential sources of information are differentiated both by their type and by their availability. On the one hand, information is either knowledge or data based, i.e. it is either stored on data carriers in the form of databases or systems or is available as knowledge in a person's memory. Second, a source is either internal or external to the company. Internal sources are exclusively accessible to the company because they are owned by the company or work for the company as employees. External sources are public and thus accessible to a wide audience despite possible restrictions.

Table 1: Possible data sources for the different objects of the data model

Source Type	Data Source	Network Level	Location Level	System Level	Process Level
Internal Data Carrier-based Information Sources	PLM	LC, PA			MT, PR, BM
	ERP	TR, TT, LC	SR, SL, PL, SP	MA, FA, FT	DE, MT, PC, PS, PR, BM
	MES			MA, MY	PS, PR
	CRM	PA	SR		DE, PR
	WMS	LC, PA, TM	SP	FA, FY	DE
	BIM	ET	PL, EP, WP, CP	MA, FA, FY	
	SCM	TR, TT, TM, ET	SL, SR, CT		DE
Internal Knowledge Carrier-Based Information Sources	F&E				PS, PR, MT, BM
	Controlling	TR	SR, SL, PS, EP, WP, CP	FA, FY	DE, MT, BM, PC, PS
	Production	LC , PA	PS, SP	MA, MY, FA, FY, FT	DE, PC, PS, PR, BM
	Sales	PA	SR		DE
	Logistics	LC, TT, PA, TM, ET	SR, SL, PS	FA, FY	DE, PC
	Facility Mgmt.	ET	PS, CP, EP, WP	MA, MY, FA, FY	
	Procurement	TM, LC, PA	SL, CT		
External Data Carrier-based Information Sources	LCA Databases	TR, TM, ET, LC, PA	PL, CT, WP, CP	FT, FY, MT	MT
	Official Statistics	TR	EP, WP, SP, CP		DE
	NGO/IGO Databases		EP, WP, CP		MT
	Standards	ET			MT
	Other Publications	TT, TM	PS, EP, WP, CP	FY, TM, MA	PC
External Knowledge Carrier-based Information Sources	Science	ET, LC, PA, TM	PL, CT, EP	FY, MY, FT	MT
	NGOs/IGOs	ET, TR	CT, CP, EP, WP		DE, MT
	Consultant	TM, ET	CT, SL, CP, EP, WP	MA, MY, FY	PC
	Associations	TR, TT, TM, ET	CT		
	Bench-marking	LC, PA, TR, TT	PL, BM	MY, FY	
	Stakeholders		CT, SL, CP, EP,WP		

Optimally, the attributes of all classes are filled for each level. Table 1 shows how the attributes can potentially be obtained from the different data sources. The attributes are marked in abbreviated form. The upper case letters correspond to the abbreviation for the class name. The meaning can be taken from the respective UML diagram in Figure 1. It should be noted that the assignment is structured generically and follows the established logic of the respective data sources. If the knowledge or data carriers are known in detail, further sources of information must be consulted and the assignments extended or adapted accordingly.

3.3 Calculation of evaluation parameters based on the data model

To calculate the evaluation parameters of the ecological sustainability of the production network the balancing idea is central, since every material does enter and leave the different boarders of the investigated system at some point. The balancing of the presented data model follows the logic shown in Figure 2. The overall balance of the production network consists of several sub-balances for the individual elements at and between the production sites. These elements correspond to the objects of the data model presented in part 3.1. For each sub-balance, both the input and the output with which the respective object interacts with the local environment must be considered. Depending on the location, the sustainability properties of the input and output vary, which also changes the sustainability indicators of the network. All balance sheet performance indicators are calculated on the basis of the objects and attributes of the data model. The variables in the formulas correspond to the attributes of the data model and adopt the notational logic already presented.

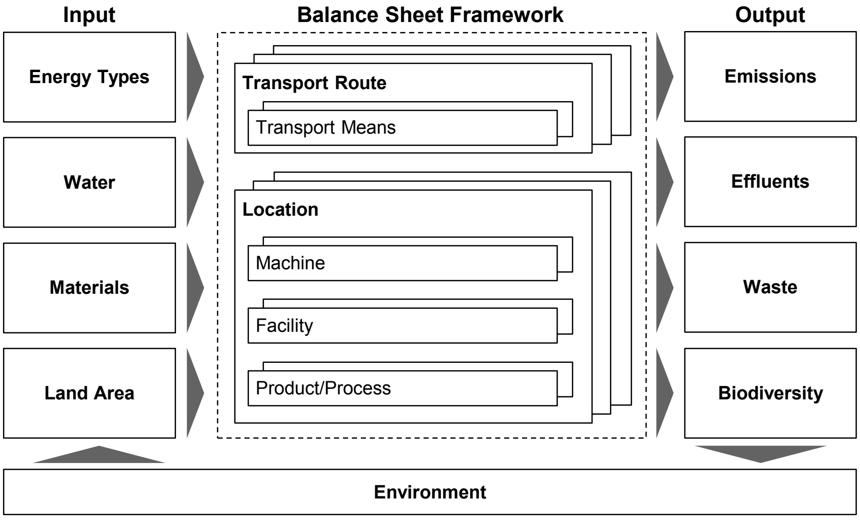

Figure 2: Balance sheet framework based on the data model for ecological sustainability evaluation

As an example the calculation of energy and emission related evaluations is presented. The calculation of the other evaluation parameters can be derived following the same logic. However, due to the limits of this publication not all formulas are published. The calculations of sustainability indicators for energy and emissions are closely linked, since greenhouse gases are generated during the conversion of primary energies to secondary energies, depending on the energy source. Figure 3 illustrates this relationship of input and output variables as well as the elements of the production network model involved.

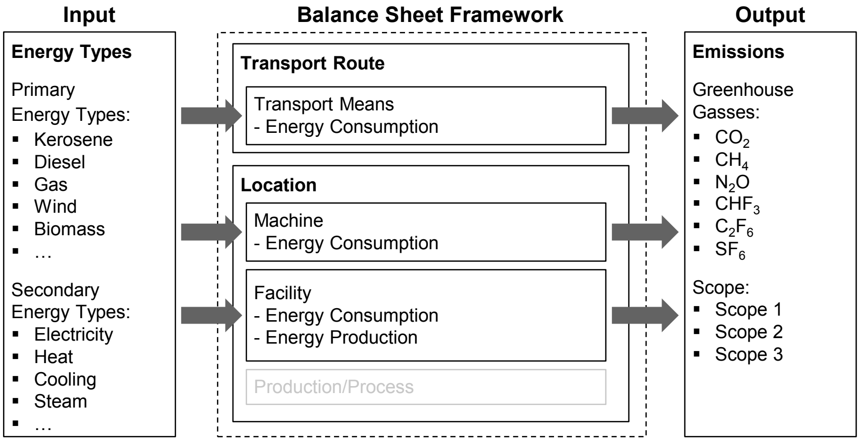

Figure 3: Balance sheet framework for the evaluation of energy and emissions

An essential key figure for the sustainability accounting of a production network is the total energy required. This is calculated using the equation in formula 1. The formula shows that, according to the model logic, there are three main types of energy consumers in the network. These are transports, machinery and facilities. The demand for transports is directly influenced by the network configuration. The demand for machines and facilities is only slightly influenced in terms of cooling and heating capacity per location. However, the type of energy sources available per site varies greatly, as shown above.

$$E_{total.} = E_{transports} + E_{machinery} + E_{facilities} \tag{1}$$

Formula 2 shows how the total energy required for transports is calculated using the data model. All variables are taken from the data model in Figure 1. According to Association of German Freight Forwarders and Logistics Operators (DSLV), the most important factors for the energy consumption of a means of transport are its capacity utilization, load type, driving style, route and traffic as well as the mass of the freight and the distance covered [24]. In practice, part of the transports are carried out by service providers, which is why real consumption values, capacity utilization as well as driving mode and traffic are unknown. Therefore, for the present model, these aspects are ignored and the density of freight is simplified to three types of cargo.

$$E_{transports} = \sum_{TR} \sum_{TT} \sum_{PR} \sum_{TM} \sum_{ET} \begin{matrix} G_{TR,TT,PR} * TTd_{TR,TS} * Tb_{TR,TT,PR,TM} * \\ (TMl_{TM} \vee TMd_{TM} \vee TMs_{TM}) * ETf_{TM,ET} \end{matrix} \tag{2}$$

Thus, in formula 2, the total energy demand is calculated by summing up the energy demand per transport route TR, track TT, product PR and the means of transport TM used as their energy types ET. Essential for this is the total weight of the transport units per product $G_{TR,TT,PR}$, which is also called the shipment weight and consists of the product and the packaging weight. This is multiplied with the distance of each track $TTd_{TR,TS}$, the binary decision variable if the track is $Tb_{TR,TT,PR,TM}$ utilized, the load specific energy consumption of the vehicle $(TMl_{TM} \vee TMd_{TM} \vee TMs_{TM})$ and the associated energy factor of the fuel $ETf_{TM,ET}$. Detailed information of each variable in the formula can be obtained from the class diagram defined in Figure 1. Some of these variables are dependent on further calculations. E.g. the shipment weight is the sum of the product weight, packaging weight and load carrier weight for each transportation unit. The packaging is used for every product unit, while the load carrier can carry as many products as defined by the transportation factor.

The presented data model in section 3.1 allows the calculation of further evaluation parameters, with limited effort regarding data procurement and implementation. The following application of the framework with a real company gives further examples on what parameters can be derived.

4. Application

The company considered for the validation is a supplier for household appliance manufacturers. Critical key figures were changed within the scope of publication for reasons of confidentiality. This has no effect on the results. The company employs over 5,000 people worldwide and generates sales of over 500 million euros. For historical reasons, the company has its roots and headquarters in Germany, but produces for its customers worldwide. The company produces at six locations: Germany, China, Austria, Turkey, Croatia and USA. In Croatia, no final products are manufactured, only components. The production network is generally based on a local-for-local configuration, although there are exceptions. For reasons of technology protection, a chemical compound is only mixed at the German site, which is a lead factory. Some stabilization rings are manufactured exclusively in Austria. Except for Germany, the temperature limiter is assembled at all sites. Germany sources this from Croatia.

Various internal and external sources were used to gather information. For example, experts from the Supply Chain department were asked about the availability of ports, rail routes and airports. The transport quantities were taken from the ERP system. The corresponding distances were determined using Google Maps and a sea distance calculator. Information on packaging and load carriers was taken from the PLM system and validated by an on-site investigation at the German locations. Information about the product and its physical properties were taken from the parts lists of the ERP system and measurements performed.

The identified key performance parameters calculated with the data model were used to identify possible courses of action. The most promising options were generated and evaluated as scenarios using a software demonstrator, which included the data model and calculation logic. The first simulated improvement action was to relocate production for the North America market from Turkey to the USA. In addition, approximately 300 tons of chemical compounds would have to be transported from Germany to the USA. The site in Turkey would take on half a million products from China as a compensation. This relocation was promising, as the environmental impact at the Chinese site is worse than in Turkey. Another improvement was offered by eliminating air freight. This reduces both greenhouse gas emissions and transportation costs. The third measure considered was the establishment of a holding plate production and stamping machine in Turkey.

The improvements that can be achieved with the three options for action presented are shown in Table 2. The results show that adapting the network improves the eco-efficiency of the energy demand by 27.8%. Even more successful is the improvement of the eco-efficiency of greenhouse gas emissions from 9,003 to 16,129 Euro revenue per emitted ton of CO2e. No improvement was achieved in water use, waste and land use. Since only one product was considered and no sites were downsized or upsized, the demand of the plants could not be changed. In addition, recycling was possible at each site, so no improvements could be achieved through product relocation.

Table 2: Evaluation and improvement of the ecological production network performance

Key Performance Indicator	Unit	Value Before Improvement	Value After Improvement	%
Eco-efficiency of Energy Demand	EUR/MWh	6,949.87	8,883.90	27.8
Eco-efficiency of Greenhouse Gas Emissions	EUR/tCO2e	9,003.31	15,961.73	77.2
Intensity of Transport	kgCO2e/tkm	0.0741	0.0174	-76.4
Eco-efficiency of Water Demand	EUR/m³	0.102	0.102	0.0
Eco-efficiency of Water Consumption	EUR/m³	-	-	-
Eco-efficiency of The Amount Of Waste For Disposal	EUR/(kg+l)	1,071.89	1,049.03	-2.1
Eco-efficiency of Hazardous Waste	EUR/(kg+l)	-	-	-
Eco-efficiency of Land Use	EUR/m2	2,120.28	2,120.28	0.0
Eco-efficiency of Potentially Species Lost	EUR/PDF	2.29E+18	2.29E+18	0.0

5. Conclusion

Global production networks are an essential component of the globalized society of the 21st century. At the same time, global production networks are also emblematic of the exponential growth of humanity over the past centuries and the resulting negative consequences for other forms of life on the planet. For this reason, the production networks of the future must not be planned and evaluated according to the premises of the past. Rather, sustainability-oriented criteria must be considered alongside competition-oriented criteria.

The present work offers an approach for this. The developed evaluation method differentiates the ecological sustainability of the input and output of production networks according to the site-specific characteristics. In this way, network planning can take into account that local limits are not exceeded and resources are only used where nature or man can provide them sustainably to a sufficient degree. The costs of transporting resources in the network are also taken into account and weighed against the advantages of local sustainability. The major influence of global production networks on sustainability is transformed from a weakness to a strength with the developed methodology. By moving production activities to an environment that can provide and process the required inputs and outputs in a sustainable manner, the ecological sustainability of products and processes will be improved without having to adapt the technology.

The developed methodology is a promising approach for assessing the ecological sustainability of production network configuration. At the same time, the methodology offers possibilities for extensions and future research activities, which could not be mapped within the scope of the present work. The isolated consideration of ecological sustainability allows a more detailed assessment, but at the same time contradicts the principle of the holistic nature of sustainability. For a complete evaluation of the sustainability of a production network, it is therefore necessary to integrate the economic and social aspects. A detailing of the data model is also conceivable, provided that the resulting effort is accepted.

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Biography

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