Development of an Optimization Method and Software for Optimizing Global Supply Chains for Increased Efficiency, Competitiveness, and Sustainability

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Abstract: Presently, an increasing human population, customer consumption, and global market competition result in the reduction of natural resources and growing environmental damage. Therefore, the current practice in the use of resources is not sustainable. The production companies have to focus not only on cost-effective and profitable operation, but at the same time environmentally friendly and sustainable production in order to increase competitiveness. New innovative technologies are required, improving the efficiency of the processes and the optimization of global supply chains (GSC) in order to establish sustainability in environmental, social, and economic aspects. The aim of the study is the GSCs’ optimization, which means forming the optimal combination of the chain members (suppliers, final assemblers, service providers) to achieve cost-effective, time-effective, and sustainable operation. This study introduces an elaborated single- and multi-objective optimization method, including the objective functions (cost, lead time) and design constraints (production and service capacities; volume of inventories; flexibility and sustainability of the chain members). Based on the elaborated method, software has been developed for the optimization of sustainable GSCs. The significance and novelty of the developed method and software is that the chain members have been required to fulfill the sustainability design constraint built into the software. A real case study is introduced, for the optimal design of a sustainable GSC, to confirm that our developed optimization method and software can be applied effectively in practice for the optimization of both profitable and sustainable GSCs.

Keywords: sustainable global supply chain; single- and multi-objective optimization method; sustainability design constraint; software application; real case study

1. Introduction

The changing global market environment, increasing human population, rapidly changing customer demands, and growing environmental damage have resulted in significant changes in the production sector. Production philosophies have changed from the traditional mass production to the Industry 4.0 concept. The supply chains have been globalized, cooperation between chain members has become more dynamic, and more complex networks of GSCs have been formed.

The supply chain is a system of supply chain members, which are production companies (suppliers, final assembler), service providers and customers as well as their production and service activities. The supply chain is the process of manufacturing finished products from natural resources, raw materials, and components and the delivery of the finished products to the end customers [1]. Continuous material and information flows and value-adding activities among the supply chain members maximize profitability and satisfy customers [2,3].
In production, the resources (raw materials, humans, machines, energy, etc.) are limited and the human population is increasing, so the current practices in the use of resources are not sustainable [1,4]. Therefore, the enterprises have to focus on cost reduction, productivity, and profitability, but at the same time have to establish environmentally friendly and sustainable production in order to increase competitiveness. New production philosophies, advanced materials, higher amounts of renewable resource usage, innovative and environmentally friendly technologies, and processes with improved efficiency and optimized GSCs are required in order to establish sustainability [1,4].

Sustainability is defined as the satisfaction of the present needs of the human population without compromising future generations’ ability to meet their own needs [5,6]. In earlier articles sustainability focused on environmental issues, but later on the ‘triple bottom line’ approach to sustainability was increasingly applied [2]. Most of the relevant literature discusses the concept of sustainability based on three main aspects as follows: Environmental, social, and economic ones. Environmental sustainability means efficiency in resource utilization, recycling and reduction of pollution, waste, and emissions [7]. The social aspect means the compliance with human rights and labor laws, the adoption of social standards (ISO 26000), and impact on local communities [8,9]. Social sustainability includes critical areas which provide health and safety, working conditions, human rights, and community programs [10,11]. The economic aspect means the achievement of the targeted long-term economic performance according to operational metrics [4,7].

Recently, several publications have criticized the above-mentioned limited interpretation of the triple bottom line. In the literature the number of publications in which the definition of sustainability is discussed in a more holistic view is increasing. For instance, in their article Ahy and Searcy concluded that the main characteristics of sustainability are economic focus, environmental focus, social focus, stakeholder focus, volunteer focus, resilience focus, and long-term focus [2].

The optimization of sustainable GSCs is part of the GSC management’s activity and is an important and essential tool for the optimal formation and operation of efficient, profitable, and sustainable GSC networks. Sustainable supply chain management means the management of material, information, and capital flows, as well as cooperation among companies along the supply chain, while taking into account goals from all three dimensions of sustainable development—economic, environmental, and social; derived from customer and stakeholder requirements [2,12,13]. The sustainable supply chain not only makes a profit, but also bears responsibility to its consumers, suppliers, societies, and environments in the innovative strategic, tactical, and management technologies employed [12,14].

The primary aim of the study is to develop an optimization method and software which provides the creation of an optimal combination for sustainable GSCs’ members (suppliers, service providers, final assemblers) to achieve not only cost-effective and time-effective but, at the same time, sustainable operation. Our developed method and software are an additional contribution to the recent state of the research field because, by the application of the software, only sustainable optimal GSCs can be created since sustainability as a design constraint is built into the method and software. Another aim of the study was to test whether our developed optimization method and software can be applied effectively in a company-based case study on the optimization of sustainable GSCs.

The significance of the topic is that the optimal formation and operation of the sustainable GSCs provide the efficiency, profitability, and sustainability of the whole GSC networks. The optimal formation of the sustainable GSC, which provides competitiveness for all members of the GSC, is an important strategical decision of the GSC management. These management decisions are supported by our method and software.

The structure of the study, main essences, and added values of the sections are the following:

1. In the literature review section, the relevant articles concerning the research topic are introduced. Based on the synthesis of the recent literature it can be concluded that, although the design of supply chains is often discussed, there is a gap in the literature in the field of optimizing sustainable GSCs. The optimization methods, which can be found in existing literature, use a limited number of design constraints. The sustainability design constraint is not taken into
consideration during the optimization, while the flexibility design constraint is available only in some publications, but in these articles the meaning of the flexibility is not detailed enough. Therefore, our developed method and software are an additional contribution to the recent state of the research field because it is the first time the literature takes sustainability and flexibility constraints into consideration simultaneously.

2. In Section 3 the our elaborated single- and multi-objective optimization method is introduced, as well as the objective functions, (1.) cost and (2.) lead time, and design constraints, (1.) capacity constraints for production and service activities, (2.) constraints for the volume of inventories, (3.) constraints for the flexibility of the chain’s members and (4.) constraints for the sustainability of the chain’s members. Software has been developed based on the elaborated optimization method, which can be applied for the optimization of profitability and at the same time as sustainable GSCs.

Our developed method and software are novel and provide an additional contribution to the recent state of the research field because, in addition to the generally applied design constraints, both sustainability and flexibility design constraints are also built into the method and software.

Sustainability design constraint means that the potential suppliers and service providers can only be members of a sustainable GSC if these companies fulfill the sustainability requirements. Since all of the members of the GSC have to fulfill the sustainability constraints, an optimal GSC can be formed by applying the software, which is not only cost- and time-effective (as in cases of the other optimizing software) but at the same time sustainable. In the literature, it is the first time that potential supply chain members’ ability to fulfill the sustainability requirements has been analyzed.

Flexibility constraint means the capability of the chain members for adapting to changing market demands. The flexibility and financial liquidity of the GSCs’ members are analyzed and evaluated. The flexibility includes the following: Resource flexibility; flexibility of the organization structure; strategic flexibility; and flexibility for collaboration between production companies, service providers, and stakeholders [15].

The systematic search method was used for single-objective optimization, while the multi-objective optimization was performed by the systematic search method combined with the normalized weighting method. In case of the multi-objective optimization, depending on the design strategy (type of final product; customers’ requirements; location of the customers; living standard of the customers; type of industrial sector; competitors’ products; etc.) the GSC management has to define whether the cost or the lead time is the more preferred design aim. Therefore, the ratio of the objective functions must be set arbitrarily in the software (e.g., 75% cost—25% lead time). In case of different ratios of the objective functions, different optimal combinations of GSCs can be formed from the same potential suppliers and service providers.

It can be concluded that the sustainability of the optimal GSCs can be provided in every kind of ratio of the objective functions, because the sustainability constraints are built into the software.

If the more important strategical aim of the management is the minimization of the total cost of the GSC, the ratio of the cost objective function has to be higher than the lead time objective function. It is often used if the most important aspect for the customers is the low cost of the products (e.g., traditional basic commodities; the customers are cost sensitive due to their living standard or their location). On the contrary if the customers are not cost sensitive (e.g., fashion industry, high-tech products, luxury products with portfolios that change very fast) but the most important requirement is the shortest delivery time, then the ratio of the lead time objective function has to be higher [1,15].

In Sections 4.3.1–4.3.4 a real case study is introduced to confirm that our developed method and software can be applied effectively, in practice, for the optimization of sustainable GSCs. A case study is introduced for the optimal design of a sustainable GSC by the selection of the optimal primary supplier, the optimal secondary supplier, and the optimal service provider (forwarding company) from more potential suppliers and service providers for three cases as follows: (1.) Total cost minimization
of the GSC, (2.) total lead time minimization of the GSC, and (3.) in case of different ratio of the objective functions (60% cost–40% lead time).

It can be concluded that our developed method and software is an additional contribution to the recent state of the research field because, by the application of the software, only sustainable optimal GSCs can be created, in case of every kind of ratio of the objective functions, since sustainability as a design constraint is built into the method and software.

2. Literature Review

A great deal of literature was evaluated relating to the research topic, which provided the theoretical background of this study. The most important logistical and production goal is maximal customer satisfaction; all of the other goals can be derived from this. Customer demands define the applied production philosophies [16]. The production philosophies have been changed from the traditional mass production to the Industry 4.0 conception. The main aim of the Industry 4.0 paradigm is the establishment of network-linked intelligent systems, which perform self-regulating production in which people, machines, equipment, and products communicate with one another. Industry 4.0 will bring the age of collaborating and intelligent industrial robots [1]. The production conceptions determine the characteristic of the supply chains [16].

2.1. Global Supply Chain Networks

The supply chain is a system of supply chain members (suppliers, final assemblers, service providers, and customers) and their production and service activities. The supply chain is the process of manufacturing finished products from natural resources, raw materials, and components and the delivery of the finished products to the end customers [1]. Global supply chains are supply chains that extend beyond a single country’s boundaries [12].

- The members of GSCs (Figure 1): Manufacturing companies [final assemblers (FA); suppliers (Sj)]; service providers (SPm) [logistics, IT, financial, etc. service providers] (detailed in Figure 2); and customers (Cj) [consumers, wholesalers, retailers, end-customer, etc.].
- The types of the service providers are the following (Figure 2): Logistics service providers (transporting, forwarding, warehousing, SC managing, etc. companies); information service providers (IT enterprises, telecommunication companies, etc.); research & development service providers (research institutes, consulting enterprises, universities, etc.); and financial service providers (lease brokers, banks, etc.).

In the last decades of the 20th century the fast-changing market environment and global competition resulted in more complex networks of supply chains. Value chains were globalized and GSC networks were formed. The cooperation between the enterprises became more dynamic. GSCs are thus characterized by focal firms that distribute across multiple countries, locate production facilities abroad, or source from offshore suppliers [17]. The focal firms seek to secure a competitive advantage by employing competent and low cost suppliers, located around the world [18]. The distance separating a focal firm and its suppliers is thus greater, as is the number of suppliers in the GSC [12].

The key of success for GSCs is to understand and fulfill customer demands. The competitiveness of the chain members originates from the utilization of the advantageous characteristics of the members. In the global market the GSCs compete together to fulfill the customer demands maximally, with high quality products or services. Customers choose between the GSCs by buying the best finished product or service. The main aspects of the customers’ decision making are the cost of the final product, total lead time, product quality, product customizability, and the quality of additional services connected to the final product.

A great deal of literature reviews the definitions, properties, and types of GSCs [19–22]. More complex GSCs have been formed and novel GSC concepts (1. Lean; 2. Agile; and 3. Hybrid)
have been established alongside the traditional chains due to fluctuating and unique customers’ needs in order to maintain and increase the competitiveness of the GSCs’ members [23].

The main goal of the Lean Supply Chain concept is to minimize waste by eliminating non-value adding activities and improving the processes continuously. The members of the lean supply chains apply the lean manufacturing philosophy, which is the most widely used conception and efficiency improvement method in many production and service sectors [24,25]. The main characteristic of Agile Supply Chains is their agility, referring to the connection between the company producing the finished product and the customer market. It means flexible adaptation to fast-changing customer demands [23,26,27]. The Hybrid Supply Chain is a combination of lean and agile supply paradigms, which utilizes the advantages of both conceptions.

![Network of a Global Supply Chain](source: Own)

**Figure 1.** Network of a Global Supply Chain. Source: Own.

Environmental damage has become a global problem and sustainability has become increasingly important. In the production sector, resources are limited and the human population is continuously increasing; therefore, recent practices in the use of resources are not sustainable.

In earlier articles the sustainability only focused on environmental issues, but later on increasingly applied the environmental, social, and economic approach to sustainability [2]. The

![Types of service providers in the GSCs](source: Own)

**Figure 2.** Types of service providers in the GSCs. Source: Own.
2.2. Sustainable Global Supply Chains

Environmental damage has become a global problem and sustainability has become increasingly important. In the production sector, resources are limited and the human population is continuously increasing; therefore, recent practices in the use of resources are not sustainable.

In earlier articles the sustainability only focused on environmental issues, but later on increasingly applied the environmental, social, and economic approach to sustainability [2]. The economic aspect means production by cost, energy, and material efficiency and innovative production technology to achieve profit. The environmental aspect means production using renewable resources and raw materials that are safe for the environment, workers, and customers. The social aspect means compliance with human rights, labor laws, and safety-at-work rules. If the GSC is completely sustainable, it will not cause damage to ecosystems or social systems and, at the same time, it will bring profits in the long term [28,29]. Presently, several articles have criticized the above-mentioned limited interpretation of the Triple Bottom Line (TBL). Elkington coined the phrase ‘TBL’ in 1994, then, in his article published in 2018, he also suggested that ‘it’s time to rethink it’ in a wider sense [30]. In the literature the number of publications in which the definition of sustainability is discussed in a more holistic view is increasing. Some studies have included further requirements for sustainability, e.g., stakeholder focus, volunteer focus, resilience focus, and long-term focus, etc. [2].

Consequently, the enterprises of the GSCs have to focus on cost reduction and profitability while also establishing environmentally friendly and sustainable production and services. Therefore, innovative and environmentally friendly technologies are needed, together with the efficiency improvement of the processes and the optimization of GSCs is required in order to establish sustainability.

Definitions and characteristics of supply chain management appear frequently in the literature. Simchi-Levi et al. defined the supply chain management as a set of approaches to integrate elements of a supply chain to minimize total system cost while maintaining adequate production and service levels [31]. There are strategic, tactical, and operational dimensions in supply chain management [32].

Sustainable supply chain management means the management of material, information, and capital flows as well as cooperation among companies along the supply chain, while taking into account goals from all three dimensions of sustainable development (economic, environmental, and social), derived from customer and stakeholder requirements [12,13].

Production companies have to establish sustainable production, while service providers have to provide sustainable services. The following two activities of sustainable GSCs are particularly damaging to the environment: (1.) Production activity of manufacturing companies (final assemblers and suppliers) of GSCs and (2.) transportation (activities of transport service providers).

2.2.1. Sustainable Production in the Global Supply Chain

The essence of sustainable manufacturing is that the hazardous impacts of manufacturing operations on the environment have to be minimized while optimizing the production efficiency of the company [33]. Sustainability orientation concerns the redesign of enterprises’ products and manufacturing processes, taking environmental and social regulations into consideration [34–36].

The Lowell Center for Sustainable Production (LCSP) defines sustainable production as the creation of goods and services using processes and systems that are non-polluting; conserving of energy and natural resources; economically viable; safe and healthful for employees, communities and consumers; and socially and creatively rewarding for all working people [37,38]. The LCSP and other authors also describes the following main elements of sustainable production as well: Energy and material use, the natural environment, social justice and community development, economic performance, workers, and products [34,37,39].
Principles of Sustainable Production

Based on the above-mentioned publications [37–39] the following nine principles of sustainable production can be summarized. The manufacturing practices relating to the nine principles of sustainable production [40] is detailed in Appendix A.

1. Sustainable design of products: Products are designed to be cost-efficient, competitive, safe, durable, and produced by energy-efficient, material-efficient, and innovative production technology (economical asp.). Furthermore, the products should be environmentally and user-friendly, easily recyclable, renewable resources will be used during the production, and the use of raw materials and final products will be safe for the environment, the workers, and the customers (environmental asp.).

2. Energy and materials efficiency during the manufacturing of products: Efficient usage of the energy and materials during the manufacturing of products from raw materials and components.

3. Elimination or recycling of wastes: Wastes and unusable by-products have to be minimized, eliminated, or recycled.

4. Substitution or elimination of hazardous materials and technologies in manufacturing processes: Chemical substances or physical agents and conditions that present hazards to human health or the environment have to be eliminated, focusing on hazardous emissions into air and water and on hazardous physical agents, technologies, or work practices.

5. Establish safe workplaces and technologies: Workplaces and technologies are designed to minimize or eliminate chemical, ergonomic, and physical hazards and to reduce the risks workers are exposed to.

6. Management activity for continuous evaluation and improvement of processes on economic, environmental, and safety aspects: Management is committed to an open and participatory process of continuous evaluation and improvement, focused on the long-term economic performance of the company. Practices are aimed at reducing environmental health and safety compliance costs, improving participatory management style, promoting stakeholder involvement in decision making, and increasing customer satisfaction; all of which enable company profitability.

7. Motivation of employees in order to improve the efficiency and creativity: Work is organized to maintain and increase the efficiency and creativity of workers. Practices aim to improve workers’ efficiency and creativity, and establish reward systems.

8. Social advantages and advancement possibilities for employees: The safety and wellbeing of all employees is a priority, as is the continuous development of their talents and capacities. It is important to provide opportunities for employee advancement, job satisfaction, training, gender equality, and reduction of turnover rate.

9. Development of community-company partnerships: The communities around workplaces are respected and enhanced economically, socially, culturally, and physically. Employment opportunities are provided for locals, developing community-company partnerships.

2.2.2. Sustainable Transport in the Global Supply Chain

Besides production activity, transportation is the other most environmentally damaging and expensive activity of GSCs. Freight transport is performed by transport service providers in GSCs.

Transportation is sustainable in the narrower sense of its environmental, social, and climate impacts, with more integrated solutions and technological innovations. In the global scope it involves the sustainability analysis of transport vehicles used for road, rail, water, or air transport, the source of energy, and the infrastructure of the transportation [41,42]. Short-term activity often promotes incremental improvements in fuel efficiency and vehicle emissions controls while long-term goals include migrating transportation from fossil-based energy to other alternatives, such as renewable energy and the use of other renewable resources [43].
There are two ways for scientific research to support sustainable and environmentally friendly transport. The first way is developing and producing environmentally friendly technologies and equipment (e.g., high-tech engines). Furthermore, scientific research can also support the cost-effective, profitable, and sustainable operation of transport service providers through efficiency improvement methods and decision-supporting software applications. These efficiency improvement methods result in the reduction of fuel consumption and environmental damage. In addition, the companies that are able to achieve higher profits can afford to invest in environmentally friendly technologies and new vehicles, which also results in the reduction of environmental damage.

Practical Tools for Sustainable Freight Transport

- Application of environmentally friendly and innovative technologies (e.g., high-tech engines);
- usage of alternatives such as renewable energy instead of fossil-based energy;
- modernization of the fleet of vehicles;
- optimized utilization of vehicle fleet capacity and human resources;
- more effective cooperation between transport modes (road, rail, water, and air) to increase the ratio of multimodal transportation (the volume of road freight transport in Europe is approximately 80% of the total freight transport volume, which makes up approximately 80% of the total emissions of the freight transportation sector; therefore, the ratio of road freight transportation has to be reduced);
- optimization of transport routes and transport trips, minimization of empty haulage;
- application of information and communication technologies (ICT);
- usage of optimization and decision-supporting software applications;
- application of waste management and recycling;
- monitoring compliance with safety-at-work rules and environmental regulations [1].

2.2.3. Optimization of Global Supply Chains

The optimization of GSCs is an important tool for optimal formation of efficient, profitable, and sustainable GSC networks. In the literature there are several optimization algorithms for network optimization, which can be classified into categories such as scalar methods, fuzzy methods, interactive methods, metaheuristic methods, decision aided methods, etc. [44].

The literature often discusses the most important objectives for supply chain optimization as objective functions as follows: Cost [27,45], profit [46], total lead time [47], customer service level [48], etc. During optimization, the design constraints also have to be defined. The most common constraints used in the design of SCs are the following: Capacity constraint for production and services, constraint for inventories, constraint for location, financial constraints, etc.

It can be concluded, based on the synthesis of the recent literature, that, although the characteristics and significance of sustainable GSCs and the design of GSCs are often discussed, there is a gap in the literature in the field of optimizing sustainable GSCs. The optimization methods, which can be found in existing literature, use a limited number of design constraints. The sustainability constraint is not taken into consideration during the optimization, while the flexibility constraint is only available in some publications, but in these articles the meaning of the flexibility is not detailed enough. Therefore, our developed method and software are additional contributions to the recent state of the research field because it is the first of the literature that takes sustainability and flexibility constraints into consideration simultaneously. This means that during the optimization the potential GSC members have been analyzed regarding their fulfillment of sustainability and flexibility requirements.
3. Single- and Multi-Objective Optimization Method and Software Application for the Design of Sustainable Global Supply Chain Networks

The single- and multi-objective optimization method was elaborated for the optimal formation of sustainable GSCs. It means that manufacturing and delivering of finished products to customers will be the most cost- and/or time-effective. During the optimization, the total cost and/or the total lead time objective functions and four design constraints, including the sustainability constraint, were defined.

3.1. Objective Functions

During the optimization of sustainable GSCs the most important objectives are the minimization of the total cost or/and the minimization of the total lead time, according to the customer satisfaction. Therefore, during the single-objective optimizations the total cost or the total lead time objective functions, while in case of the multi-objective optimization the total cost and the total lead time objective functions, were taken into consideration.

In our study we focused on the main part of the GSCs, from the raw material suppliers to the final assemblers, taking the activities of the service providers into consideration. The relation between the final assemblers and customers is beyond the scope of this paper.

Indices used in the mathematical formulations are the following:

- $i$: Product identifier;
- $j$: supplier identifier (primary, secondary, raw material, etc. suppliers);
- $k$: final assembler identifier;
- $l$: customer identifier;
- $m$: service provider identifier;
- $t$: time interval;
- $FA$: final assembler;
- $S$: supplier; and $SP$: service provider.

3.1.1. Total Cost Objective Function

The total cost of the GSCs, including the production costs, raw material costs, component costs, transportation costs, inventory costs, and costs of service providers (Equations (2)–(6)).

$$f_1 = CP + CM + CT + CI + CS.$$  
(1)

- **Total production cost**: The summation of manufacturing costs at $S$s and $FA$s, as follows:

$$CP = \sum_t \sum_j \sum_i cp_{ij} Qt_{ijt} + \sum_t \sum_k \sum_i cp_{ik} Qt_{ikt},$$  
(2)

where $cp_{ij}$ is the unit production cost of parts of final product $i$ at $S$s; $cp_{ik}$ is the unit production cost of final product $i$ at $FA$s; $Qt_{ijt}$ is the production quantity of parts of final product $i$ at $S$s during time period $t$; and $Qt_{ikt}$ is the production quantity of final product $i$ at $FA$s during time period $t$.

- **Total cost of raw materials and parts** is the summation of material costs at $S$s and $FA$s, as follows:

$$CM = \sum_t \sum_j \sum_i cm_{ij} Qt_{ijt} + \sum_t \sum_k \sum_i cm_{ik} Qt_{ikt},$$  
(3)

where $cm_{ij}, cm_{ik}$ are the unit material costs and $Qt_{ijt}, Qt_{ikt}$ are the production quantities.

- **Transportation cost** is the summation of cost of transportation between the manufacturing companies of the supply chain (between $S$s; between $S$s and $FA$s), as follows:

$$CT = \sum_t \sum_k \sum_j \sum_i ct_{ijk} Qt_{ijk} + \sum_t \sum_k \sum_i ct_{ikl} Qt_{iklt},$$  
(4)

where $ct_{ijk}, ct_{ikl}$ are the unit transportation costs; and $Qt_{ijk}, Qt_{iklt}$ are the volumes of goods.
• **Inventory cost** is the summation of inventory costs at manufacturing companies of the supply chains (at Ss and FAs) as follows:

\[
CI = \sum_{t} \sum_{j} \sum_{i} c_{ij}l_{ijt} + \sum_{t} \sum_{k} \sum_{i} c_{ik}l_{ikt},
\]

where \(c_{ij}, c_{ik}\) are the unit inventory costs; and \(l_{ijt}, l_{ikt}\) are the volumes of goods to be stored.

• **Cost of service activities at service providers** (e.g., packaging, labelling, documentation, financing, etc.), as follows:

\[
CS = \sum_{t} \sum_{m} \sum_{i} C_{spimt},
\]

where \(C_{spimt}\) is the cost of activities of SPs needed for production of final product \(i\).

### 3.1.2. Total Lead Time Objective Function

The total lead time of the GSCs, including the production lead times at Ss and FAs, the lead times of services at SPs, the lead times of warehousing, and the lead times of transportation (Equations (8)–(11)) as follows:

\[
f_2 = TP + TS + TW + TT.
\]

• **Total production lead time** is the summation of manufacturing lead times at production enterprises of the supply chains (Ss and FAs), as follows:

\[
TP = \sum_{t} \sum_{j} \sum_{i} t_{p_{ij}} Q_{ijt} + \sum_{t} \sum_{k} \sum_{i} t_{p_{ik}} Q_{ikt},
\]

where \(t_{p_{ij}}, t_{p_{ik}}\) are unit production lead times; and \(Q_{ijt}, Q_{ikt}\) are production quantities.

• **Total service lead time** is the summation of time consumptions of activities of service providers of the supply chains required for manufacturing (packaging, labeling, etc.), as follows:

\[
TS = \sum_{t} \sum_{m} \sum_{i} T_{spimt}.
\]

• **Total warehousing time** is the summation of the storage times at the members of the supply chains (Ss, FAs and SPs), as follows:

\[
TW = \sum_{j} \sum_{i} t_{w_{ij}} + \sum_{k} \sum_{i} t_{w_{ik}} + \sum_{m} \sum_{i} t_{w_{im}}.
\]

• **Total transport time** is the sum of transportation times of loading units, between Ss and FAs, as follows:

\[
TT = \sum_{k} \sum_{j} \sum_{i} t_{l_{ikj}}.
\]

### 3.2. Design Constraints

During the single- and multi-objective optimization the following 4 design constraints were defined: (1.) Constraints for production and service capacities, (2.) constraints for the volume of inventories, (3.) constraints for the flexibility of the chain’s members, and (4.) constraints for the sustainability of the chain’s members.

#### 3.2.1. Production and Service Capacity Constraints

Limitations have to be defined for the minimal volume of the production at production companies of the GSCs (Ss and FAs), as follows:

\[
Q_{ijt}^{\text{min}} \leq Q_{ijt},
\]
Limitations have to be defined for the minimal volume of the service capacities at service providers of the GSCs (SPs), as follows:

\[ Q_{ikt}^{\text{min}} \leq Q_{ikt}. \]  

(13)

The minimum values of capacities relating to the chain’s members provide the continuous operation of the GSCs.

### 3.2.2. Inventory Constraints

The volume of inventories has to be limited at production companies and service providers of the GSCs (Ss, FAs and SPs), as follows:

\[ I_{ijt}^{\text{min}} \leq I_{ijt} \leq I_{ijt}^{\text{max}}; I_{ikt}^{\text{min}} \leq I_{ikt} \leq I_{ikt}^{\text{max}}; I_{imt}^{\text{min}} \leq I_{imt} \leq I_{imt}^{\text{max}}. \]  

(15)

The minimum values of the inventories provide the continuous operation of the GSCs, the maximum values provide that the loss will be minimized in the chains (the stock is a typical type of waste according to lean philosophy).

### 3.2.3. Flexibility Constraints

Responsiveness and flexibility of the companies have become key characteristics for being profitable. Supply chains adapt to the rapidly changing market demands if they are flexible, so flexibility is essential to increase or maintain competitiveness. Chan et al. [15] gave definitions and characteristics for the following flexibilities: Manufacturing flexibility, strategic flexibility, resource flexibility, coordination flexibility, range flexibility, and response flexibility.

In our conception the following flexibility constraints are defined for the chain’s members:

- **Flexibility of the manufacturing system** at the manufacturing companies (capability for producing high variety of goods in type and volume continuously) (FA and Ss), as follows:
  
  \[ FL_{ijt}^{\text{min}} \leq FL_{ijt}; \]
  
  (16)

\[ FL_{ikt}^{\text{min}} \leq FL_{ikt}. \]  

(17)

- **Flexibility of the service providers** (capability for providing continuous, reliable, high quality and high variety of services in type and volume) (SPs), as follows:

  \[ FL_{imt}^{\text{min}} \leq FL_{imt}. \]  

(18)

- **Financial liquidity** of all of the chain’s members (high flexibility requires investment), as follows:

  \[ LI_{ijt}^{\text{min}} \leq LI_{ijt}; LI_{ikt}^{\text{min}} \leq LI_{ikt}; LI_{imt}^{\text{min}} \leq LI_{imt}. \]  

(19)

The flexibility constraints can be given by a value in a given interval (1–5) based on a complex evaluation. These values are also taken into consideration in the software application.

### 3.2.4. Sustainability Constraints

Sustainability performance measurement and evaluation of the production companies and service providers is a complex task. Key Performance Indicators (KPI) are efficient tools for performance measurement of production and logistics activities. KPIs provide high transparency of the processes, since processes that can be measured can be improved. In our conception, the sustainability requirements are taken into consideration in all of the three aspects, environmental,
social, and economic, according to the most of the relevant publications in recent literature. Based on these issues the sustainability of all companies can be evaluated by KPIs. In the literature there are a lot of suggestions for the performance measurement of the sustainability. Ad J. de Ron offered the following issues for the performance measurement of sustainability: Cost awareness, process quality, product quality, energy usage, recovery rate, and life cycle performance [49].

In practice, the most often applied KPIs, according to the literature, are the following: e.g., The ratio of material recycling and reuse; the amount of material usage (raw materials, components); the ratio of advanced materials; the ratio of energy- and material-efficient final products; the ratio of renewable energy; the ratio of energy-efficient production technologies; the utilization of resources; energy consumption; energy saving; amount of emissions; the product recycling rate; waste reduction rate; waste recycling rate; amount of hazardous substances/chemicals; volume of noise and vibration; measurement of safety and health of workers; worker satisfaction; and training and career development programs [34,40–42].

In the developed method and software, the following sustainability constraints are defined for the chain’s members:

- **Sustainability of the manufacturing companies** of the global supply chains (FA and Ss), as follows:
  \[ SS_{ijt}^{\text{min}} \leq SS_{ijt}, \quad (20) \]
  \[ SS_{ikt}^{\text{min}} \leq SS_{ikt}. \quad (21) \]

- **Sustainability of the service providers** of the global supply chains (SPs), as follows:
  \[ SS_{imt}^{\text{min}} \leq SS_{imt}. \quad (22) \]

The sustainability constraints can be given by a value in a given interval (1–5) based on a complex evaluation. These values are also taken into consideration in the software application.

### 3.3. Optimization Method

The single-objective optimization (cost or lead time objective functions) is achieved by the systematic search method.

The elaborated multi-objective formulation takes Equations (1) and (7) as the objective functions, \( f_1 \) and \( f_2 \). The multi-objective optimization problem can be expressed as follows:

\[
\min_{x \in Q} \{ f_1(x), f_2(x) \},
\]

where \( x \) is the vector of decision variable and \( Q \) is the space of feasible solutions.

The multi-objective optimization is performed by the systematic search method. The normalized weighting method is also applied to analyze the weights (ratio) of the objective functions (cost and lead time) in the optimization.

\[
f(x) = \frac{1}{2} \sum_{\alpha=1}^{2} \frac{w_\alpha f_\alpha(x)}{f_\alpha^0} \quad \text{where} \quad w_\alpha \geq 0 \quad \text{and} \quad \sum_{\alpha=1}^{2} w_\alpha = 1,
\]

where \( f_\alpha(x) \) are the objective functions and \( w_\alpha \) are the weights of the objective functions. The condition \( f_\alpha^0 \neq 0 \) is assumed.

In case of the multi-objective optimization due to the weighting method, depending on the design strategy (type of final product; customers’ requirements; location of the customers; life standard of the customers; type of industrial sector; competitors’ products; etc.) the manager has to define whether the minimization of the cost or the lead time is the more important design aim. Therefore, the ratio of the objective functions must also be given.
3.4. Software for Optimization of Sustainable Global Supply Chains

Software has been developed based on the elaborated optimization method, which can be applied for the optimization of profitable and sustainable GSCs. The software has been developed in the Java programming language.

Introduction of the Software Conception

- The process of the optimization can be seen in Figure 3, according to the software main screen of the Figure 4.
- The main screen of the developed software application can be seen in Figure 4.

![Figure 3. Process of the optimization based on the software screen. Source: Own.](image)

![Figure 4. Main screen of the software.](image)
4. Discussion—Main Significant Added Value of Our Developed Optimizing Method and Decision Supporting Software—Confirmed by a Real Case Study

The main aims of the research were the following:

• The primary goal was to develop an optimization method and software which provides the creation of optimal GSCs’ networks that are not only cost-effective and time-effective, but at the same time sustainable. With the software only optimal sustainable GSCs can be created, since sustainability, as a design constraint, is built into the method and software.

• Another aim was to ensure that different optimal combinations of GSCs can be formed from the same potential suppliers and service providers, even in case of different ratios of the objective functions (cost, lead time). The ratio of the objective functions can be set arbitrarily in the software depending on the design strategy (type of final product; customers’ requirements; location of the customers; living standard of the customers; type of industrial sector; competitors’ products; etc.) of the GSC management. If the management’s strategic aim is to minimize the total cost of the GSC, the ratio of the cost objective function will be higher than the lead time objective function. It is often used if the most important aspect for the customers is the low cost of the products (e.g., the final products are traditional basic commodities; the customers are cost-sensitive due to their living standard or their location). However, if the customers are not especially cost-sensitive and the most important requirement is, rather, the shortest delivery time (total lead time), then the ratio of the lead time objective function will be higher. This strategy is used in cases including the fashion industry, high-tech products, and luxury products, whose portfolio changes very quickly due to their short life cycle. Thus, the sustainability of the optimal GSCs can be provided in every kind of ratio of the objective functions because the sustainability design constraints are built into the method and the software.

• A further aim of the study was to use a real case study to confirm that the developed optimization method and software can achieve the two before-mentioned aims, i.e., the software can be applied effectively in practice for the optimization of sustainable GSCs.

4.1. Main Significant Added Value of Our Developed Optimizing Method and Decision Supporting Software Compared to Other Optimizing Methods and Software Applications

Although the existing literature often discusses the design of supply chains, there is a gap in the literature in the field of optimizing sustainable GSCs. The optimization methods which can be found in the existing literature use a limited number of design constraints. The sustainability design constraint is not taken into consideration at all during the optimization. Only a few publications refer to the flexibility design constraint, but in these articles the meaning of flexibility is not discussed in enough detail. Therefore, our developed method and software make a novel contribution to the recent state of the research field, as it is the first time in the literature that sustainability and flexibility design constraints are taken into consideration simultaneously. This means that during the optimization the potential supply chain members have been analyzed regarding their fulfillment of sustainability and flexibility requirements.

• During optimization the sustainability design constraints are taken into consideration and built into the method and software, in addition to the generally applied design constraints (e.g., production and service capacities, limitations for the volume of inventories, etc.). The potential suppliers and service providers can only be members of a sustainable GSC if these companies fulfill the sustainability requirements. Both the sustainability of the production companies and the sustainability of the service providers are analyzed and evaluated. Since all of the members of the GSC have to fulfill the sustainability constraints, by applying the software an optimal GSC can be formed which is not only cost- and time-effective and profitable (as in the case of the other optimizing software) but, at the same time, also sustainable. In the literature this is the first
time the potential supply chain members’ ability to fulfill the sustainability requirements has been analyzed.

- Depending on the design strategy (type of final product; customers’ requirements; location of the customers; living standard of the customers; type of industrial sector; competitors’ products, etc.) of the GSC management, the ratio of the cost and lead time objective functions can be set arbitrarily in the software. Therefore, with the software, an optimal sustainable GSC can be formed according to the individual demand of the final assembler. Depending on the ratio of the objective functions the optimal combinations of the sustainable GSC members will differ. The most important advantage of our method and software is that the sustainability of the optimal GSCs can be provided in case of every kind of ratio of the objective functions because the sustainability design constraints are built into the software.

- During the optimization the flexibility design constraints are also taken into consideration in the method and built into the software. Flexibility means the capability of the supply chain members for adapting to changing customer and market demands. Flexibility design constraints are the following: (1) Constraint for the flexibility of the manufacturing systems (machines, technologies, etc.) at production companies, (2) flexibility constraint for the service providers (primarily focusing on forwarding enterprises, which are the most expensive and environmentally damaging service providers) and (3) financial liquidity constraint for the production companies and service providers. The flexibility includes the following: Resource flexibility, flexibility of the organization structure, strategic flexibility, and flexibility for collaboration between manufacturing enterprises, service providers, and stakeholders.

- The software provides the opportunity to select the required transport modes (road, rail, air, and water) in all relations between the potential suppliers and between the potential suppliers and the final assembler of GSCs. Consequently, the sustainable transport chains can be configured preferring environmentally friendly transport modes (water, rail) to minimize environmental damage, noise, and air pollution in the GSCs by the selection of the optimal service providers (transport companies).

- Our developed software is user friendly, easy to use, and customizable based on user demands.

4.2. Positive Effects of the Application of the Our Developed Method and Decision Supporting Software on the Sustainable GSCs’ Operation

- The method and the software support the decision making of the management in the formation and analysis of the potential GSC alternatives and analyze the ability of the potential manufacturing companies (suppliers) and service providers to fulfill all of the design constraints, involving sustainability requirements as well.

- The method and the software support the decision making of the management in the selection of the optimal GSC (involving optimal suppliers and service providers) after the evaluation of the GSC alternatives.

- The software supports the analysis and evaluation of the different shoring and sourcing strategies (e.g., offshoring, outsourcing, offshore outsourcing, reshoring, etc.). The potential chain members and their parameters and the distances between the members and the applied transport modes (rail, road, water, air) can be given arbitrarily in the software. During the optimization, based on the before-mentioned input data, the optimal partners can be selected at the same time taking into consideration the positive and negative effects of different shoring and sourcing strategies on the GSCs’ sustainability [50].

- The method and the software provide the formation of long-term strategic partnerships between the GSC’s members and the long-term predictability of the sustainable GSC.

- The risks and losses are minimized in the sustainable GSC.

- The stakeholders’ and customers’ satisfaction increases.
• The method and the software provide fast reconfiguration of the GSC in case of the changing of the parameters (input data) by the members.
• The profit at all of the GSC’s members is maximized.

4.3. Real Case Study for Optimization of a Sustainable Global Supply Chain

In this section a real case study is introduced for the optimal design of a sustainable GSC by the selection of the optimal primary supplier, the optimal secondary supplier, and the optimal service provider (forwarding company) from several potential suppliers and service providers.

Three optimal GSCs are searched in the case study for three cases as follows: (1.) Total cost minimization of the GSC (single-objective cost optimization); (2.) total lead time minimization of the GSC (single-objective lead time optimization); and (3.) a different ratio of the objective functions (multi-objective cost-lead time optimization: 60% cost–40% lead time).

4.3.1. Problem Description

The goal is the formation of an optimal sustainable GSC of a final assembler (FA). The potential members of the chain are 4 potential primary suppliers (S11, S12, S13, S14); 5 potential secondary suppliers (S21, S22, S23, S24, S25); and 3 potential forwarding service providers (SP1, SP2, SP3) (Figure 5).

One optimal primary supplier, one optimal secondary supplier, and one optimal forwarding service provider have to be selected to form the optimal sustainable GSC.

4.3.2. Input Data for the Calculation

Relation Matrix

Relations of the final assembler, potential primary suppliers, potential secondary suppliers, and potential service providers can be given by a relation matrix \( R \), as follows:

\[
R = \begin{bmatrix}
1 & \cdots & \cdots & n \\
\vdots & & & \\
1/0 & & & \\
\vdots & & & \\
n & & & \\
\end{bmatrix}
\]

• \( n \): identifiers of final assembler, potential suppliers and potential service providers,
• value of elements of the matrix is 0 (there isn’t relation between members) or 1 (there is relation between members).

Table 1 shows the relation matrix of the members of the GSC.
Table 1. Relation matrix of the global supply chain’s members.

<table>
<thead>
<tr>
<th></th>
<th>FA</th>
<th>S₁¹</th>
<th>S₁²</th>
<th>S₁³</th>
<th>S₁⁴</th>
<th>S₂¹</th>
<th>S₂²</th>
<th>S₂³</th>
<th>S₂⁴</th>
<th>S₂⁵</th>
<th>S₃¹</th>
<th>S₃²</th>
<th>S₃³</th>
</tr>
</thead>
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<td>1</td>
<td>1</td>
<td>0</td>
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<td>S₁³</td>
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<tr>
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<tr>
<td>S₂⁵</td>
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<tr>
<td>S₃¹</td>
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<tr>
<td>S₃²</td>
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<tr>
<td>S₃³</td>
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<td>1</td>
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<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Distance Matrix

The distances between the final assembler and potential suppliers can be given by the following matrix \( L \).

\[
L = \begin{bmatrix}
1 & \ldots & \ldots & n \\
\vdots & \ddots & \ddots & \vdots \\
n & \ldots & \ldots & 1
\end{bmatrix}
\]

- elements of the matrix are the transport distances between the members of the GSC [km].

Table 2 shows the distance matrix of the members of the global supply chain.

Table 2. Distance matrix [Km].

<table>
<thead>
<tr>
<th></th>
<th>FA</th>
<th>S₁¹</th>
<th>S₁²</th>
<th>S₁³</th>
<th>S₁⁴</th>
<th>S₂¹</th>
<th>S₂²</th>
<th>S₂³</th>
<th>S₂⁴</th>
<th>S₂⁵</th>
<th>S₃¹</th>
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</tr>
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<tbody>
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<td>1234</td>
<td>12,611</td>
<td>11,395</td>
<td>19,925</td>
<td>12,660</td>
<td>18,565</td>
<td>11,879</td>
<td>15,553</td>
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<tr>
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<tr>
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<td>15,723</td>
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<td>10,921</td>
<td>15,937</td>
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<td>1527</td>
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<td>11,208</td>
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<td>12,719</td>
<td>10,921</td>
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<td>10,489</td>
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<td>10,302</td>
<td>15,243</td>
<td>11,208</td>
<td>15,618</td>
<td>0</td>
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<td></td>
</tr>
</tbody>
</table>

Further Input Data for the Calculations

Table 3 shows the data relating to the final assembler, potential primary suppliers, potential secondary suppliers, and potential service suppliers. Table 3 includes the unit production costs, the unit material costs, the unit production lead times, the maximal production capacities, and the maximal storage capacities at the final assembler and at the potential suppliers, furthermore the flexibility, the liquidity, and the sustainability parameters of the final assembler, the potential suppliers, and the potential service providers.

The specific transportation cost \( c_t \) in the case of road transport is 0.00024 Eur/piece/Km, in the case of water transport is 0.00012 Eur/piece/Km, in the case of rail is 0.00016 Eur/piece/Km, and in the case of air transport is 0.00058 Eur/piece/Km.
Table 3. Input data for the calculation.

<table>
<thead>
<tr>
<th>Unit Production</th>
<th>Unit Manufacturing</th>
<th>Unit Production</th>
<th>Storage Capacity at the</th>
<th>Flexibility of the</th>
<th>Liquidity</th>
<th>Sustainability of the</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost ( c_{p,j,k} ) [Eur/pieces]</td>
<td>Cost ( c_{m,j,k} ) [Eur/pieces]</td>
<td>Lead Time ( t_{p,j,k} ) [hour]</td>
<td>Capacity ( Q_{j,k} ) [pieces/week]</td>
<td>Member ( I_{j,k} ) [unit load]</td>
<td>Member ( F_{j,k,m} )</td>
<td>Member ( L_{j,k,m} )</td>
</tr>
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<td>FA 120</td>
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<td>30</td>
<td>4500</td>
<td>7000</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>S11 50</td>
<td>50</td>
<td>10</td>
<td>2500</td>
<td>4000</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>S12 50</td>
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<td>12</td>
<td>2500</td>
<td>3500</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>S13 28</td>
<td>30</td>
<td>10</td>
<td>2500</td>
<td>5000</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>S14 35</td>
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<td>8</td>
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<td>4000</td>
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<td>5500</td>
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<td>3</td>
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<td>4500</td>
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</tr>
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<td>S18 25</td>
<td>16</td>
<td>12</td>
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<td>5000</td>
<td>3</td>
<td>3</td>
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<td>17</td>
<td>1100</td>
<td>3500</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>SP1 -</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>SP2 -</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>SP3 -</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>
4.3.3. Run of the Optimization Software

At first the input data of the case study have to be given according to the Menu 1–3 of the main screen (Figure 4). After that, the objective function(s) have to be selected and the minimal values of the design constraints and the production volume have to be given in the Menu 4. (Figure 4).

Input Data Given

1. *Data for the products to be produced* (Menu 1.): the characteristics of the finished product have to be given:
   - Dimension of the final product,
   - BOM (bill of material),
   - unit load dimensions and weights.

2. *Data for potential members of the supply chain* (Menu 2.): The unit production costs, the unit material costs, the unit production lead times, the maximal production capacities, and the maximal storage capacities at the final assembler and at the potential suppliers, furthermore, the flexibility, the financial liquidity, and the sustainability parameters of the final assembler, the potential suppliers, and the potential service providers have to be given according to the data of Table 3.

3. *Relations for members of the supply chain* (Menu 3.—Figures 6 and 7): The relation matrix (Table 1), the distance matrix (Table 2), and the transport modes (road, rail, air, and water) applied for the transportation of goods between all of the relations have to be given.

[Figure 6. Parameter setting of the relation matrix.]

[Figure 7. Given elements of the distance matrix.]
The software also provides the possibility of precise determination (distances and transit times) of the transport modes (road, rail, air, and water) in all relations between the potential suppliers and between the potential suppliers and the final assembler (Figure 7).

There is a very good opportunity to configure sustainable transport chains preferring environmentally friendly transport modes (water, rail) to minimize environmental damage, noise, and air pollution in the GSCs.

4.3.4. Run Results of the Optimization Software

Results of the optimization (Menu 4.—Figure 8): The total cost or/and total lead time objective function(s) (Equations (1) and (7)) can be selected.

In case of the multi-objective optimization due to the weighting method, which depends on the preferred design aim, the weights of the objective functions can be set arbitrarily (in the case study cost: 60%—lead time: 40%). In this study, at first the single-objective optimization than the multi-objective optimization will be shown.

The minimal values for the design constraints (Equations (12)–(14) and (16)–(22)) can also be set by the supply chain manager in this menu (Figure 8), as follows: Our project includes the flexibility of the production companies (value: 3), the flexibility of the service providers (value: 4), the liquidity of all of the companies (value: 3), the sustainability of the manufacturing companies (value: 4), and the sustainability of the service providers (value: 4).

The production volume also has to be given (in 1000 units of final products).

5. Results of the Single- and Multi-Objective Optimizations of the Sustainable Global Supply Chains

In this section the results of the optimization are described. Three optimal sustainable GSCs have been searched for three cases, as follows: (1.) Total cost minimization of the GSC (single-objective cost optimization); (2.) total lead time minimization of the GSC (single-objective lead time optimization); and (3.) a different ratio of the objective functions (multi-objective cost-lead time optimization: 60% cost–40% lead time).
5.1. Single-Objective Cost Optimization—The Optimal Sustainable Global Supply Chain

Figure 9 shows the result of the optimization for minimal cost. The possible six GSCs that fulfill all of the design constraints are listed on the right side of the print screen. These GSC alternatives are also visualized graphically in Figure 9.

Supplier S25 and service provider SP3 cannot fulfill the sustainability requirements, while supplier S22 cannot fulfill either the sustainability constraint or the production capacity constraint. Therefore, these three companies are not eligible to be members of the GSC.

The optimal sustainable GSC formation, which provides the minimal total cost in our case study, is the following: FA – S14 – S21 (colored in green in Figure 9). The total cost of the final product is 297 EUR/unit in the optimal GSC.

The optimal forwarding company is the SP2, which provides the most cost effective and sustainable transportation in the optimal GSC between FA – S14 – S21.

![Figure 9. Optimal sustainable GSC in case of single-objective cost optimization.](image)

5.2. Single-Objective Lead Time Optimization—The Optimal Sustainable Global Supply Chain

Figure 10 shows the result of the optimization for minimal lead time. The possible six GSCs that fulfill all of the design constraints are listed on the right side of the print screen. These GSC alternatives are also visualized graphically in Figure 10.

Supplier S25 and service provider SP3 cannot fulfill the sustainability requirements, while supplier S22 cannot fulfill either the sustainability constraint or the production capacity constraint. Therefore, these three companies are not eligible to be members of the GSC.

The optimal sustainable GSC formation which provides the minimal total lead time in our case study is the following: FA – S11 – S24 (colored in green in Figure 10). The total lead time of one piece of a final product is 564 [hour] in case of the optimal GSC.

The optimal forwarding company is the SP2, which provides the most time effective and sustainable transportation in the optimal GSC between FA – S11 – S24.
5.3. Multi-Objective Optimization—Optimal Sustainable Global Supply Chain

The software application provides the possibility for multi-objective optimization (total cost, total lead time). During multi-objective optimization, the systematic search method, combined with a normalized weighting method, was applied to analyze the weights (ratio) of the objective functions.

In case of the multi-objective optimization, depending on the design strategy (type of final product; customers’ requirements; location of the customers; life standard of the customers; type of industrial sector; competitors’ products; etc.) the GSC manager has to define the more preferred design aim and the ratio of the cost objective function and lead time objective function.

In the case study, the ratio of the objective functions was defined as follows: 60% cost–40% lead time. The result of the multi-objective optimization can be seen in Figure 11. The optimal sustainable GSC formation which provides a 60% cost–40% lead time ratio of objective functions in the case study is the following: FA – S12 – S23 (in Figure 11 colored by green).

The optimal forwarding company is the SP2, which provides the required cost–time effective and sustainable transportation in the optimal GSC between FA – S12 – S23.
5.4. Summary of the Optimization Results

From the case study the following results can be summarized:

- In case of different ratios of the objective functions (cost, lead time) different optimal combinations of sustainable GSCs can be formed from the same potential suppliers and service providers (Figures 9–11). The ratio of the objective functions depends on the design strategy (type of final product; customers’ requirements; location of the customers; living standard of the customers; type of industrial sector; competitors’ products; etc.) of the GSC management.

- The sustainability of the optimal GSCs can be provided in every kind of ratio of the objective functions, because the sustainability design constraints for manufacturing companies and service providers are built into the method and the software. Therefore, all of the three above-described optimal GSCs are sustainable.

- In all three cases the same forwarding company was selected as the optimal service provider providing the most sustainable services. Thus, environmental damage, noise, and air pollution were minimized in the sustainable GSCs.

6. Conclusions, Limitations and Future Research

Presently, in production, the resources are limited, there is an increasing human population, market competition, and environmental damage, therefore current practices in the use of resources are not sustainable. New innovative and environmentally friendly technologies, efficiency improvement, and the optimization of production and logistical processes are required. The production companies have to establish not only cost-effective and profitable, but at the same time, sustainable production.

The optimization of sustainable GSCs is an important and essential tool for optimal formation and operation of efficient, profitable, and sustainable GSC networks.

In the study a single- and multi-objective optimization method was elaborated for the optimal design of sustainable GSC networks, which provides the creation of the optimal combination of sustainable GSCs’ members to achieve not only cost-effective and time-effective, but at the same time, sustainable operation. During the optimization the objective functions of (1.) total cost and/or (2.) lead time and the four design constraints, (1.) capacity constraints for production and service activities, (2.) constraints for the volume of inventories, (3.) constraints for the flexibility of the chain’s members, and (4.) constraints for the sustainability of the chain members, are considered.

The systematic search method was used for single-objective optimization, while the multi-objective optimization was performed by the systematic search method combined with the normalized weighting method. In the case of multi-objective optimization, due to the weighting method and depending on the design strategy, the GSC management has to define the ratio of the cost objective function and lead time objective function.

Software has been developed based on the elaborated optimization method. With the software a sustainable optimal GSC can be formed according to the individual demand of the final assembler. Due to the normalized weighting method, the weights of the objective functions have to be set arbitrarily in the software.

Our developed method and software are an additional contribution to the recent state of the research field because it is the first of the literature to take sustainability and flexibility design constraints into consideration simultaneously and build them into the method and software.

Flexibility constraint means the capability of the chain members to adapt to changing market demands. Flexibility and financial liquidity of the GSCs’ members are analyzed and evaluated. The flexibility includes the following: Resource flexibility; flexibility of the organization structure; strategic flexibility; and flexibility for collaboration between production companies and service providers.

Sustainability design constraint means that the potential suppliers and service providers can only be members of an optimal sustainable GSC if these companies fulfill the sustainability requirements. Since all of the members of the GSC have to fulfill the sustainability constraints, by applying the
software, an optimal GSC can be formed which is not only cost- and time-effective (as in case of the other optimizing software) but at the same time sustainable.

A real case study was introduced to confirm that our developed optimization method and software can be applied effectively in practice for the optimization of sustainable GSCs. In a case study, the optimal design of a sustainable GSC was described by the selection of the optimal primary supplier, the optimal secondary supplier, and the optimal service provider (forwarding company) from more potential suppliers and service providers for three cases, as follows: (1.) Total cost minimization of the GSC; (2.) total lead time minimization of the GSC; and (3.) in case of different ratio of the objective functions (60% cost–40% lead time). It can be concluded that, depending on the ratio of the objective functions, the optimal combinations of the sustainable GSC’s members are different (Figures 9–11).

It can be summarized that our developed method and software are an additional contribution to the recent state of the research field, because, by the application of the software, only sustainable optimal GSCs can be created, in case of every kind of ratio of the objective functions, since sustainability as a design constraint is built into the method and software.

The limitation of our developed software is that, among the activities of the service providers, only the activities of transport service providers have been taken into consideration during the calculation of total cost and total lead time of the GSC, as transportation is the most environmentally damaging and expensive activity in sustainable GSCs. Further service providers would be taken into account in the future to define the total costs and lead times of the GSCs more precisely.

The research introduced in the recent article can be continued by the development of optimization methods and software applications which are specialized for the optimization of sustainable GSCs of different industrial sectors requiring other objective functions or, further, more specific design constraints.

Author Contributions: Conceptualization, G.K., B.I.; literature review, data collection, B.I.; methodology, software, G.K.; writing—original draft preparation, G.K., B.I.; writing—review and editing, G.K., B.I. All two authors have read and approved the final manuscript.

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Appendix A

The manufacturing practices relating to the nine principles of sustainable production are the following: (In the Section 2.2.1. Sustainable Production in the Global Supply Chain) [37–40].

1. Sustainable design of products

   • Practical tools for sustainable production [40]:
     • Application of advanced materials and innovative and green production technologies; design of energy, material, and cost-efficient products;
     • hazardous substances substitution or elimination in products and processes;
     • considerations regarding disassembly, reuse, and recycling during product design;
     • eco-design assisted by customers;
     • recyclability and reuse of incoming materials packaging and packaging minimization.

2. Energy and materials efficiency during the manufacturing of products

   • Practical tools for sustainable production [40]:
     • Mapping energy consumption for identifying energy saving possibilities;
     • use of renewable energy; application of energy-efficient manufacturing systems;
• equipment upgrades for improving efficiency; preventive equipment maintenance;
• employee training on energy savings; energy audits;
• material recycle and reuse; material substitution for better efficiency;
• material usage optimization; process optimization.

3. Substitution or elimination of hazardous materials and technologies in manufacturing processes

• Practical tools for sustainable production [40]:
  • Hazardous substances substitution or elimination in production processes;
  • tracking chemicals in processes and products; heavy metals filtration;
  • training of workers on hazardous substances;
  • application of closed-loop process water systems.

4. Elimination or recycling of wastes

• Practical tools for sustainable production [40]:
  • Component and product design optimization; substitution of hazardous materials;
  • redesigning of components to reduce solid waste; non-conforming products reduction;
  • reuse and recycle of direct and indirect waste; external and internal recycling;
  • donation of waste and by-products to other industries or institutions.

5. Establish safe workplaces and technologies

• Practical tools for sustainable production [40]:
  • Robotic automation in hazardous activities; mechanical lifting aids;
  • internal safety inspections; external work environment audits;
  • employee rotation among work stations; employee training on hazardous risks;
  • process modifications to reduce noise and vibration.

6. Management activity for continuous evaluation and improvement of processes from economic, environment, and safety aspects

• Practical tools for sustainable production [40]:
  • Strategic sustainability and functional goals are displayed throughout the plant;
  • technology investment prioritization considering environment, safety, quality, and economic aspects; communicating with employees about strategic plans, targets, and results;
  • ISO 9001 for continuous managerial evaluation.

7. Motivation of employees in order to improve the efficiency and creativity

• Practical tools for sustainable production [40]:
  • Work standardization; work accountability;
  • employee improvement suggestions goals; team work; improvement meetings;
  • rewards for applicable improvement suggestions from employees.

8. Social advantages and advancement possibilities for employees

• Practical tools for sustainable production [40]:
• Health and safety management system; employee rotation;
• training plans; career development programs; job satisfaction assessment;
• scholarships; subsidies for health and well-being purposes;
• performance appraisal; ISO 9001 supporting training and competence.

9. Development of community-company partnership

• Practical tools for sustainable production [40]:
  • Job opportunities for locals; collaboration with educational institutions;
  • periodical meetings with local authorities; volunteer work within local communities.

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