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Using Pareto Optimization to Support Supply Chain Network Design within Environmental Footprint Impact Assessment

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Abstract: A product environmental footprint is a multi-criteria measure for environmental sustainability. Most of these environmental criteria are either synergies (non-trade-offs) or compromises (trade-offs) within environmental metrics. This forms a multi-objective problem of supply chain network design. The product environmental footprint is an aid or tool that enterprises may use to measure and improve the life cycle environmental performance of their products. In this research, a multi-criteria method, Pareto optimization, is used to design a supply chain network based on the results of a product environmental footprint. In Pareto optimization, two objectives are formulated: Environmental impact and cost. Using the results of this research, designers will be able to choose a material with a lower environmental impact and supply chain managers will be able to select suppliers with lower environmental impacts. A case study of industry practice is also analyzed. It shows an environmental footprint is useful for the supply chain design network.

Keywords: life cycle assessment; environmental footprint; supply chain network design; multi-objective optimization

1. Introduction

To reduce environmental impacts, several environmental footprints have been developed for enterprises to use in measuring aspects of environmental performance, such as the carbon footprint (CF) (ISO 14067: 2018) and water footprint (WF) (ISO 14046: 2014). In the past, these footprints provided significant contributions for assisting enterprises in obtaining measurements and achieving reductions in different markets [1,2]. However, given the existence of a variety of footprint indicators that measure single or collective pressures arising from production and consumption, an enterprise must choose only some of them to address the significant anthropogenic impacts on the ecosystem [3]. Therefore, it is necessary to develop an integrated footprint.

Product environmental footprints (PEFs) are used as criteria for environmental sustainability. Most of these criteria are either synergies (non-trade-offs) or compromises (trade-offs) within environmental metrics. For example, photovoltaics show synergies in the CF, WF, NF (nitrogen footprint), and ENF (energy footprint). In addition, when an enterprise attempts to improve the life cycle environmental performance of a product, most research highlights two objectives that must be addressed simultaneously: Lowered cost (the economic aspect) and reduced environmental impacts. This creates a multi-objective optimization (MOO) problem in a supply chain network design [4]. Supply chain network design, which determines the infrastructure and physical structure of a supply chain, is also called strategic supply planning [5], and covers the issues of efficiency and risk under uncertainty [6].

This research investigates a bi-objective optimization problem related to the design of a supply chain network to solve this trade-off problem. MOO is also used to determine the best solutions for the problem while considering the suppliers' existing constraints [7], which include the suppliers' environmental impacts, cost, and production capacities. The supply chain network design is determined through resolution of the MOO problem, which also allows selection of appropriate suppliers based on low environmental impact and cost.

The structure of this paper is as follows. First, a literature review on environmental footprints is presented. The next section describes the research methods used in this study. Finally, the empirical data are analyzed, and conclusions are drawn.

2. Literature Review

The goal of the literature review is to review relevant background material so as to identify gaps, weaknesses, problems or controversies that need to be addressed. The literature review is presented in two parts. The first part introduces the concept of a product environmental footprint, while the second part examines design for product environmental footprints.

2.1. Introduction of Product Environmental Footprints

The concept of an environmental "footprint" originated in 1992 based on the term "ecological footprint" [8]. Footprints can be presented as the planet's boundaries, comprised of its biophysical subsystems or processes. Many footprints exist; however, not all have a standard and clear definition. Čuček et al. [9] summarized existing footprints based on a triple bottom line: economic, environmental, and social footprints. Product environmental impacts should consider the product's whole life cycle through the methodology of life cycle analysis. The 14 impacts of the environmental footprint include: climate change, ozone depletion, human toxicity, cancer effects, non-cancer effects, particulate matter, ionizing radiation HH, photochemical ozone formation, acidification, terrestrial eutrophication, freshwater eutrophication, freshwater eco-toxicity, land use, water resource depletion, and mineral, fossil, and resource depletion. Table 1 shows the impact assessment model as updated in 2018 [10]. Based on the product environment guide [11], the PEF was initiated with the aim of developing a harmonized European methodology for environmental footprint (EF) studies that can accommodate a broader suite of relevant environmental performance criteria using a life-cycle approach. This methodology also considers ISO standards: ISO 14044 [12], ISO/DIS 14067 [13], ISO 14025 [14], ISO 14020 [15], greenhouse gas (GHG) protocol, the specification for assessment of the life cycle GHG emissions of goods and services [16], and the International Reference Life Cycle Data System (ILCD) handbook [17], among others.

Table 1. Product environmental footprint (PEF) Methodology.

NO	Impact Category	Impact Assessment Model	Impact Category Indicators
1	Climate Change	Global Warming Potentials (GWP) over a 100 year time horizon. IPCC 2013	kg CO_2 equivalent
2	Ozone Depletion	EDIP model based on the ODPs of the World Meteorological Organization (WMO) over an infinite time horizon.	kg CFC-11 equivalent
3	Ecotoxicity for aquatic fresh water	USEtox model	CTUe (Comparative Toxic Unit for ecosystems)
4	Human Toxicity—cancer effects	USEtox model	CTUh (Comparative Toxic Unit for humans)

Table 1. *Cont.*

NO	Impact Category	Impact Assessment Model	Impact Category Indicators
5	Human Toxicity—non-cancer effects	USEtox model	CTUh (Comparative Toxic Unit for humans)
6	Particulate Matter/Respiratory Inorganics	Fantke et al. (2016) in UNEP (2016)	kg PM2.5 equivalent
7	Ionising Radiation—human health effects	Human Health effect model	Kg U235 equivalent
8	Photochemical Ozone Formation	LOTOS-EUROS model	kg NMVOC equivalent
9	Acidification	Accumulated Exceedance model	mol H+ eq
10	Eutrophication—terrestrial	Accumulated Exceedance model	mol N eq
11	Eutrophication—aquatic (fresh water)	EUTREND model	kg P equivalent
12	Resource Depletion—water	Available WAter Remaining (AWARE) model (UNEP 2016).	kg world deprived
13	Resource Depletion—fossil	CML method v. 4.8 (2016)	MJ
14	Land Transformation	LANCA LCIA model (as in Bos et al., 2016)	Kg

2.2. Designing for Product Environmental Footprint

It is very important to systematically evaluate the product's environmental footprint in the early design stage [18]. Previously, designers used qualitative and subjective methods that drew on their extensive experience and knowledge, such as checklists or design guidelines, to evaluate qualitative attributes for their environmental impacts [19–21]. However, as quantitative methods and tools have been further developed, designers have begun adopting these tools to support their design decisions, footprints, or determine the indicators of potential environmental impacts. These quantitative tools, the bottom-up life cycle assessment (LCA) and top-down input-output analysis (IOA), are important methodologies that support both designers and supply chain managers in decision making.

A significant number of studies are related to decreasing the environmental footprints of products. There are three approaches to decreasing an environmental footprint: low environmental impact (1) material substitution, (2) manufacturing process substitution, and (3) logistics design, such as low environmental impact supplier substitution. Together, these form a low carbon supply chain network design. A supply chain can be seen as a network of actors that perform the functions of product development, procurement of material from suppliers, movement of material between facilities, manufacturing and product distribution of finished goods to customers, and after-market support for sustainment [22,23]. Based on this definition, environmental impacts could be reduced through supplier integration [24].

Normally, it is difficult to evaluate a product's environmental footprint during the concept design phase, since there may only be a rough idea of the solution without adequate and accurate operational data [25]. To solve this problem, Song and Lee [26] developed a low carbon product system that includes GHG-BOM (Bill of Material), estimation of the product's GHG emissions, identification of problematics parts. Kuo et al. [1] developed a CO_2 predictive system based on the depth-first search in the early design stage, while Hitchcock [27] developed low carbon and green supply chains. Yang et al. [28] used bilinear non-convex mixed integer programming, which was reduced to a pure linear mixed integer model for a low-carbon city logistics distribution network design. Kawasaki et al. [29] constructed a model to simulate the relationship of CO_2 emissions, cost, and lead time. Tseng and Hung [30] developed an objective function that considered the operations and social costs of CO_2 emissions, allowing evaluation of carbon emissions in greater detail through the life cycle stages. In Kuo et al.'s [31] model, a low carbon supply chain network was optimized based on carbon emissions, cost, and suppliers' manufacturing capacities. However, when trade-offs exist between different life cycle stages or different product environmental footprints, a challenge remains.

In summary, two foundational research issues have been studied in relation to sustainable design synthesis to reduce environmental impacts [18]. One addresses the means by which a sustainable design can be created for a product's environmental footprint and the generation of feasible solutions through design synthesis. The second, existing design methodology for determining low product environmental footprints, still lacks an optimal solution for the product life cycle.

3. Research Methods

3.1. Pareto-Optimal Solutions

Multi-objective optimization problems involve more than one objective function that is to be minimized or maximized. The answer is a set of solutions that define the best trade-off between competing objectives. There are some multi-objective methods such as the weighted sum method, weighted metric method. The challenge for the multi-objective is how to define the best trade-off between competing objectives. One way to resolve multi-objective problems is by using Pareto-optimal solutions. Normally, a multi-objective optimization problem can be formally defined as in Equation (1):

$$\begin{aligned} \min_{x \in X^{n_x}} \quad & f(x) = \{f_1(x), f_2(x), \ldots, f_M(x)\} \\ & \text{s.t.} \\ & \qquad g(x) \leq 0 \\ & \text{and} \\ & \qquad h(x) = 0 \end{aligned} \tag{1}$$

where x is the vector of decision variables bounded by the decision space, X^{n_x}, and f is the set of objectives to be minimized [32]. The functions $g(x)$ and $h(x)$ respectively represent the sets of inequality and equality constraints that define the feasible region of the n_x-dimensional continuous or discrete space. To solve a multi-objective optimization problem, Messac et al. [33] proposed the normal constraint method for generating a set of evenly spaced solutions on a Pareto frontier. The seven steps of the normal constraint method to generate a set of evenly spaced solutions on a Pareto frontier are as follows. *Utopia line* refers to the line joining two anchor points in bi-objective cases, where anchor point is defined as minimizer of the specific objective function with no regard to other objectives. *Utopia hyperplane* refers to the plane that comprises all the anchor points in the multi-objective case.

Step 1. Obtain anchor points,
Step 2. Objective mapping/normalization,
Step 3. Generate Utopia line vector,
Step 4. Normalize increments,
Step 5. Generate Utopia line points,
Step 6. Pareto point generation, and
Step 7. Pareto design metric values.

3.2. Variables

In this section, the symbol, parameter, and decision variable are introduced (Table 2).

Table 2. Summary of symbols

Symbol	Description
i	i^{th} supplier, $S = \{1, \ldots, i\}$
j	j^{th} transportation mode, $T = \{1, \ldots, j\}$
K	k^{th} material/components, $R = \{1, \ldots, k\}$
a	a^{th} production line, $L = \{1, \ldots, a\}$
b	b^{th} process, $M = \{1, \ldots, b\}$
Parameter	
EF_{ijk}	Environmental impacts of i^{th} supplier, j^{th} transportation mode, and k^{th} material/component
μ	Total material demand
a_{ik}	Amount for i^{th} supplier with k^{th} material/component
TKM_{ik}	Ton-kilometer for i^{th} supplier with k^{th} material/component
EA	Total environmental impact for the sub material
ER_{ik}	Environmental impact for i^{th} supplier with k^{th} material/component
W_k	Weight of the k^{th} material/component
D_i	Distance of the i^{th} supplier
ET_j	Environmental impact for the j^{th} mode of transportation
EP	Environmental impact of Taiwan power
EM	Total Environmental impact of the process
M_{ab}	Power required for a^{th} production line in b^{th} process
ESR_{ik}	Environmental impact of i^{th} supplier with k^{th} sub material
$TSKM_{ik}$	Ton-kilometer *for* i^{th} supplier with k^{th} sub material
WS_k	Weight of k^{th} sub material
DS_i	Distance of the i^{th} sub material supplier
EST_j	Environmental impact of the j^{th} transportation mode of sub material
$Cost_{ijk}$	Cost of i^{th} supplier, j^{th} transportation mode, and k^{th} material/component
CM	Total manufacturing cost
CA	Total sub material cost
CR_{ik}	Cost for the i^{th} supplier with k^{th} material/component
CT_j	Cost of the j^{th} transportation mode
CP	Cost of the Taiwan power
CSR_{ik}	Cost for the i^{th} supplier with k^{th} sub material/component
CST_j	Cost of j^{th} transportation mode of sub material
P_{ik}	Capacity of the i^{th} supplier with k^{th} material/component
Decision variable	
X_{ijk}	Amount of i^{th} supplier, j^{th} transportation mode, and k^{th} material/component

3.3. Product Environmental Footprint Minimization and Cost Minimization

Suppose the supply chain manufacturer tries to minimize total environmental impacts and cost simultaneously, based on the quantity of material/components, transportation distance, power consumption of the manufacturing process, and production capacity of the supplier. Basically, the Product's Environmental Footprint (PEF) is equal to as Equation (2):

$$\text{PEF} = \text{AD} \times \text{EF} \quad (2)$$

where

AD: activity data, collected (measured, calculated, or estimated) from production sites associated with the unit processes within the system boundary

EF: emission factor, data derived from databases

3.3.1. Product Environmental Footprint

The EF is defined as follows. Equation (3) is the sum of the environmental impacts of raw material usage and processes.

$$\text{Min } Z_1 \sum_{k\in R} \frac{\sum_{i\in S}\sum_{j\in T} EF_{ijk} \times X_{ijk}}{\mu} + EM \tag{3}$$

where EF_{ijk} represents the environmental impacts for the raw material, and EM for the environmental impacts for the manufacturing process.

The supply chain manager will consider that the different materials in different production lines using different processes will have varied environmental impacts. Equation (4) is the sum of the environmental impacts of the manufacturing activities, machining processes, and so on.

$$EM = \sum_{a\in L}\sum_{b\in M} M_{ab} \times EP \tag{4}$$

The supply chain manager will also consider the environmental impacts of the main and sub materials. Equation (4) is the sum of the environmental impacts of raw material usage and processes, where ER_{ik} is the environmental impact for the i^{th} supplier with the k^{th} material/components, TKM_{ik} is ton-kilometers for the i^{th} supplier with the k^{th} material/components, ET_j is the environmental impact for the j^{th} transportation mode, and EA is the total environmental impact for sub materials, Equations (5)–(8).

$$EF_{ijk} = ER_{ik} + (TKM_{ik} \times ET_j) + EA \quad \forall i \in S\ j \in T\ k \in R \tag{5}$$

TKM_{ik}, is weight for the k^{th} material/component

$$TKM_{ik} = W_k \times D_i \quad \forall i \in S\ k \in R \tag{6}$$

$$EA = \sum_{k\in R}\sum_{i\in S}\sum_{j\in T} ESR_{ik} + TSKM_{ik} \times EST_j \tag{7}$$

$$TSKM_{ik} = WS_k \times DS_i \quad \forall i \in S\ k \in R \tag{8}$$

3.3.2. Cost

Cost is defined as follows. Equation (9) is the sum of the environmental impacts of raw material usage and processes.

$$Min\ Z_2 \sum_{k\in \mathrm{R}} \frac{\sum_{i\in S}\sum_{j\in T} Cost_{ijk} \times X_{ijk}}{\mu} + CM, \tag{9}$$

where CM = cost of total power consumption.

During the manufacturing process, the cost of different materials varies at different production lines using different processes. Equation (10) is the cost of total power consumption. Equations (10)–(11) are the costs of the main raw material, transportation, and sub materials.

$$CM = \sum_{a\in L}\sum_{b\in M} M_{ab} \times CP \tag{10}$$

$$Cost_{ijk} = CR_{ik} + \left(TKM_{ik} \times CT_j\right) + CA \quad \forall i \in S\ j \in T\ k \in R \tag{11}$$

$$CA = \sum_{k\in R}\sum_{i\in S}\sum_{j\in T} CSR_{ik} + TSKM_{ik} \times CST_j \tag{12}$$

3.3.3. Constraints

Equations (13)–(15) are the constraints for total cost and environmental impacts. Equation (13) shows that supply usage should be equal to that of demand. Equation (14) shows that total demand should be less than suppliers' total production capacity, while Equation (15) shows that the supplier should provide a certain amount to be available for purchase.

$$\sum_{i\in S}\sum_{j\in T}\sum_{k\in R} X_{ijk} = \mu \quad (13)$$

$$\sum_{i\in S}\sum_{j\in T} X_{ijk} \leq P_{ik} \quad (14)$$

$$\sum_{i\in S}\sum_{j\in T} X_{ijk} \geq a_{ik} \quad (15)$$

4. Case Study

In this research, a case study is conducted of a type of gardening equipment, a gardening shear. The company is located in northern Taiwan. The scope of the life cycle inventory in this research is defined by the phrase, "from cradle to gate". Figure 1 shows the production road map. Thus far, there is no product category rule for the gardening shear. The raw material includes 1 primary kind of material and 45 kinds of sub material. There are 51 suppliers that can supply the 46 materials.

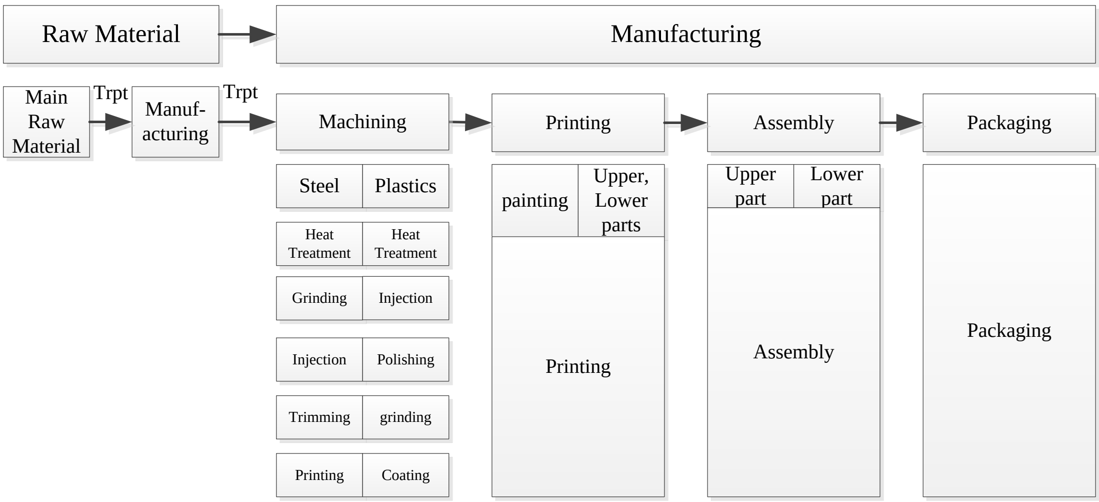

Figure 1. Production road map.

4.1. Data Collection

To reduce environmental impacts, there are three alternatives that allow designers to select a suitable material: hot rolled steel, forged steel, and SK 85 fiber reinforced plastic. The production capacities for these three types of material are also limited to 75,000 pcs, 25,000 pcs, and 75,000 pcs, respectively. The total marketing demand is 100,000 pcs/month. To calculate the environmental footprint of the gardening equipment, the material data is extracted from the bill of material (BOM) in the enterprise resource planning system. The electricity usage is calculated based on the Tai-electricity bill in Taiwan. The ILCD 2011 midpoint method version 1.01 in SimaPro software is used to calculate the environmental impact [34]. The following data are collected from the case study. There are six different types of transportation: a truck weighing less than 3.5 tons (T1), a 3.5 ton truck (T2), an 11 ton truck (T3), a 15 ton truck (T4), sea transportation to Tokyo (T5), and sea transportation to Geneva (T6). Table 3 shows the suppliers for different materials as well as their transportation method. Most suppliers are located in Taiwan; however, S6 and S8 are outside of Taiwan.

Table 3. Data of the material/component supplier.

Supplier	Material	Transportation	Material/ Component	Supplier	Material	Transportation	Material/ Component
S1	R1	T3	hot rolled steel	S27	R24	T2	Lubricating oil
S2	R2	T4	forged steel	S28	R25	T2	Lubricating oil
S3	R3	T2	fiber reinforced plastic	S29	R26	T2	Lubricating oil
S4	R4	T2	Plastics (A)	S30	R27	T2	Lubricating oil
S5	R5	T2	Plastics (B)	S31	R28	T1	Printing
S6	R6	T6	Printing (A)	S32	R29	T1	Printing
S7	R6	T2	Printing (A)	S33	R30	T1	Printing
S8	R7	T6	Printing (B)	S34	R31	T1	Printing
S9	R7	T2	Printing (B)	S35	R32	T1	Oil
S10	R8	T2	Coating X	S36	R33	T2	Packaging A
S11	R9	T2	Coating Y	S37	R34	T2	Packaging B
S12	R10	T2	Steel sand (A)	S38	R35	T1	Packaging C
S13	R11	T2	Steel sand (B)	S39	R36	T2	Packaging D
S14	R12	T1	Screw	S40	R37	T2	Packaging E
S15	R13	T1	Nut	S41	R38	T2	M3 screw
S16	R14	T1	Spring	S42	R39	T1	Packaging G
S17	R15	T2	Switch	S43	R40	T1	Packaging H
S18	R16	T1	Lubricating oil	S44	R41	T2	Packaging I
S19	R17	T5	Oil for treatment	S45	R42	T2	Packaging J
S20	R18	T2	Grinding tool (A)	S46	R43	T2	Packaging K
S21	R18	T2	Grinding tool (B)	S47	R44	T1	Tape 1.5 cm
S22	R19	T2	Lubricating oil	S48	R44	T1	Tape 1.5 cm
S23	R20	T2	Lubricating oil	S49	R45	T1	Tape 2 cm
S24	R21	T2	Lubricating oil	S50	R45	T1	Tape 2 cm
S25	R22	T2	Lubricating oil	S51	R46	T1	PE film
S26	R23	T2	Lubricating oil				

Table 4 shows the supplier travel distance. Here, the ton-km is a unit of freight carriage that is equal to the transportation of one metric ton of freight over a distance of one kilometer. Table 5 shows the cost and weight of different materials, and Table 6 shows the cost of different transportation types.

Table 4. Data of supplier travel distance.

Supplier	Distance	Ton-km	Supplier	Distance	Ton-km	Supplier	Distance	Ton-km
S1	21.1	4.90×10^{-3}	S18	1.4	2.23×10^{-8}	S35	1.5	8.31×10^{-10}
S2	36.6	8.50×10^{-3}	S19	1450.91	1.66×10^{-4}	S36	2.3	1.07×10^{-5}
S3	24.7	5.74×10^{-3}	S20	25.1	2.87×10^{-6}	S37	20	1.51×10^{-4}
S4	1.3	4.72×10^{-5}	S21	144	1.70×10^{-4}	S38	6.2	4.96×10^{-6}
S5	30.2	1.10×10^{-3}	S22	17.2	2.35×10^{-5}	S39	19.8	1.65×10^{-4}
S6	9447.23	1.35×10^{-2}	S23	26.5	1.45×10^{-6}	S40	10.2	1.01×10^{-4}
S7	19.4	2.77×10^{-5}	S24	17.2	1.26×10^{-6}	S41	10.2	1.45×10^{-4}
S8	9447.23	1.35×10^{-2}	S25	26.5	2.15×10^{-6}	S42	8.4	1.81×10^{-6}
S9	34.3	4.89×10^{-5}	S26	17.2	1.79×10^{-6}	S43	8.4	1.08×10^{-6}
S10	7.3	1.58×10^{-6}	S27	16.1	5.08×10^{-6}	S44	10.2	4.89×10^{-6}
S11	7.3	1.24×10^{-5}	S28	17.2	5.42×10^{-6}	S45	10.2	3.93×10^{-6}
S12	24.8	1.32×10^{-3}	S29	6.8	2.77×10^{-7}	S46	21.2	3.17×10^{-6}
S13	36.3	1.96×10^{-3}	S30	5.9	2.30×10^{-7}	S47	13.8	5.21×10^{-6}
S14	5.6	4.59×10^{-5}	S31	156	4.68×10^{-7}	S48	27.2	1.03×10^{-5}
S15	5.6	1.26×10^{-5}	S32	156	2.11×10^{-7}	S49	13.8	3.38×10^{-6}
S16	14	1.68×10^{-5}	S33	16.7	1.50×10^{-7}	S50	27.2	6.65×10^{-6}
S17	12.1	4.34×10^{-5}	S34	16.7	3.76×10^{-7}	S51	27.2	9.19×10^{-7}

Table 5. Cost and weight of different materials.

Material	Cost USD	Weight ton	Environmental Impact (PT)	Material	Cost USD	Weight ton	Environmental Impact (PT)
R1	0.139	2.32×10^{-4}	2.23×10^{-4}	R24	0.0182	3.16×10^{-7}	2.73×10^{-7}
R2	1.500	2.32×10^{-4}	3.77×10^{-4}	R25	0.0182	3.15×10^{-7}	2.72×10^{-7}
R3	5.066	2.32×10^{-4}	3.36×10^{-5}	R26	0.0001	4.07×10^{-8}	9.37×10^{-9}
R4	0.0602	3.63×10^{-5}	7.68×10^{-6}	R27	0.0001	3.91×10^{-8}	8.98×10^{-9}
R5	0.0603	3.64×10^{-5}	7.70×10^{-6}	R28	0.0002	3×10^{-9}	2.52×10^{-9}
R6	0.0327	1.43×10^{-6}	7.52×10^{-7}	R29	0.0000	1.35×10^{-9}	5.52×10^{-10}
R7	0.0326	1.43×10^{-6}	8.44×10^{-7}	R30	0.0001	9.01×10^{-9}	1.54×10^{-9}
R8	0.0078	2.16×10^{-7}	1.97×10^{-8}	R31	0.0001	2.25×10^{-8}	4.11×10^{-9}
R9	0.0615	1.7×10^{-6}	1.76×10^{-5}	R32	0.0000	5.54×10^{-10}	6.33×10^{-11}
R10	2.7380	5.33×10^{-5}	2.06×10^{-5}	R33	0.0026	4.67×10^{-6}	2.89×10^{-6}
R11	2.7787	5.41×10^{-5}	2.09×10^{-5}	R34	0.0432	7.53×10^{-6}	3.20×10^{-6}
R12	0.0049	8.19×10^{-6}	3.17×10^{-6}	R35	0.0005	8×10^{-7}	3.10×10^{-7}
R13	0.0014	2.25×10^{-6}	8.73×10^{-7}	R36	0.0019	8.32×10^{-6}	1.24×10^{-9}
R14	0.0007	1.2×10^{-6}	4.65×10^{-7}	R37	0.0857	9.86×10^{-6}	4.19×10^{-6}
R15	0.0782	3.58×10^{-6}	5.18×10^{-7}	R38	0.0399	1.43×10^{-5}	6.06×10^{-6}
R16	0.0001	1.6×10^{-8}	3.67×10^{-9}	R39	0.0121	2.15×10^{-7}	3.68×10^{-8}
R17	0.0000	1.14×10^{-7}	3.07×10^{-8}	R40	0.0072	1.28×10^{-7}	2.20×10^{-8}
R18	0.0203	1.18×10^{-6}	2.52×10^{-6}	R41	0.0045	4.79×10^{-7}	1.28×10^{-7}
R19	0.0234	1.37×10^{-6}	2.91×10^{-6}	R42	0.0005	3.85×10^{-7}	1.64×10^{-7}
R20	0.0002	5.46×10^{-8}	6.96×10^{-9}	R43	0.0009	1.49×10^{-7}	4.48×10^{-8}
R21	0.0003	7.32×10^{-8}	9.33×10^{-9}	R44	0.0046	3.78×10^{-7}	8.44×10^{-9}
R22	0.0003	8.13×10^{-8}	1.08×10^{-8}	R45	0.0023	2.45×10^{-7}	5.47×10^{-9}
R23	0.0004	1.04×10^{-7}	1.27×10^{-8}	R46	0.0001	3.38×10^{-8}	1.26×10^{-8}

Table 6. Cost of different transportation types.

Transportation Type	Environmental Impact Coefficient (PT)	Cost (USD)	Transportation Type	Environmental Impact Coefficient (PT)	Cost (USD)
T1	2.17×10^{-5}	0.0002	T4	3.16×10^{-5}	0.0005
T2	9.26×10^{-5}	0.0002	T5	6.60×10^{-7}	0.0009
T3	3.16×10^{-5}	0.0004	T6	6.60×10^{-7}	0.0007

5. Results

5.1. The EF Impacts

The environmental impacts are calculated based on ILCD 2011 midpoint method in Simapro software. From the lifecycle stages, most of the EF impacts are found in the raw material and manufacturing stages. Among the EF impacts in Table 7, the most significant impacts are human toxicity, non-cancer effects, and freshwater eco-toxicity. In Table 8, hot rolled steel has higher EF impacts when compared to the other two materials. However, from the perspective of climate change, forged steel has the lowest impact.

Table 7. Environmental footprint (EF) of different life cycle stages.

EF impacts	Raw Material	Transportation	Manufacturing	PT sub sum
Climate change	1.18×10^{-5}	6.43×10^{-8}	3.07×10^{-5}	4.25×10^{-5}
Ozone depletion	2.63×10^{-7}	4.77×10^{-9}	5.10×10^{-7}	7.78×10^{-7}
Human toxicity, cancer effects	4.99×10^{-5}	2.5×10^{-7}	9.53×10^{-5}	1.46×10^{-4}
Human toxicity, non-cancer effects	4.58×10^{-4}	6.56×10^{-7}	3.91×10^{-4}	8.49×10^{-4}
Particulate matter	1.75×10^{-5}	6.74×10^{-8}	4.55×10^{-5}	6.31×10^{-5}
Ionizing radiation	9.67×10^{-6}	3.87×10^{-8}	5.32×10^{-5}	6.3×10^{-5}
Photochemical ozone formation	9.2×10^{-6}	4.11×10^{-8}	1.54×10^{-5}	2.47×10^{-5}
Acidification	1.18×10^{-5}	4.32×10^{-8}	2.58×10^{-5}	3.76×10^{-5}
Terrestrial eutrophication	4.45×10^{-6}	2.02×10^{-8}	9.52×10^{-6}	1.4×10^{-5}
Freshwater eutrophication	1.95×10^{-5}	4.06×10^{-8}	1.31×10^{-4}	1.5×10^{-4}
Freshwater ecotoxicity	1.93×10^{-4}	4.58×10^{-7}	1.54×10^{-4}	3.47×10^{-4}
Land use	1.32×10^{-6}	2.55×10^{-8}	2.02×10^{-6}	3.37×10^{-6}
Water resource depletion	1.7×10^{-5}	8.39×10^{-10}	1.50×10^{-6}	1.85×10^{-5}
Mineral, fossil & ren resource depletion	3.88×10^{-5}	6.07×10^{-7}	7.16×10^{-6}	4.65×10^{-5}
Total	8.42×10^{-4}	2.32×10^{-6}	9.62×10^{-4}	0.001806

Table 8. EI impacts of different main materials.

EF Impacts	Hot Rolled Steel	Forged Steel	Fiber Reinforced Plastics
climate change	6.8733×10^{-6}	2.3608×10^{-5}	1.3600×10^{-5}
Ozone depletion	2.0890×10^{-7}	4.8042×10^{-7}	2.2070×10^{-5}
Human toxicity, cancer effects	9.0739×10^{-5}	2.2070×10^{-5}	4.5100×10^{-5}
Human toxicity, non-cancer effects	8.6656×10^{-4}	7.6869×10^{-5}	7.5500×10^{-4}
Particulate matter	1.3881×10^{-5}	5.6298×10^{-6}	3.1500×10^{-5}
Ionizing radiation	4.0372×10^{-6}	2.9980×10^{-5}	3.2500×10^{-6}
Photochemical ozone formation	5.2598×10^{-6}	9.2187×10^{-6}	1.4200×10^{-5}
Acidification	6.7801×10^{-6}	9.0564×10^{-6}	1.3000×10^{-5}
Terrestrial eutrophication	2.9140×10^{-6}	4.8086×10^{-6}	6.6700×10^{-6}
Freshwater eutrophication	2.2870×10^{-5}	1.0753×10^{-5}	3.5300×10^{-5}
Freshwater ecotoxicity	6.2722×10^{-4}	2.9393×10^{-5}	9.3700×10^{-5}
Land use	9.3035×10^{-7}	1.0000×10^{-6}	2.0000×10^{-6}
Water resource depletion	6.2908×10^{-6}	7.1959×10^{-5}	3.8600×10^{-6}
Mineral, fossil & ren resource depletion	4.1665×10^{-5}	2.4473×10^{-5}	4.6900×10^{-5}
Total	$\mathbf{1.70 \times 10^{-3}}$	$\mathbf{3.19 \times 10^{-4}}$	$\mathbf{1.09 \times 10^{-3}}$

5.2. The Pareto Frontier

From the calculation, the first objective is to minimize total environmental impact, which is 121.4 PT. The second objective is to minimize total cost, which is 1,067,316 USD. The Pareto frontier is then divided by 20 points, which is shown in Table 9. The reason why it is divided by 20 points is to be equally distributed. The designer can determine his or her priority based on the sequence of hot rolled steel, fiber reinforced plastics, and forged steel, as shown in Figure 2.

Table 9. The Pareto frontier.

	Environmental Impact (PT)			Cost (USD)	
Objective 1	121.4			1,397,085	
Objective 2	137			1,067,316	
Point	Cost	EF	Point	Cost	EF
1	32,392,000	137	11	37,659,461	127.27
2	32,918,867	135.92	12	38,186,269	126.66
3	33,445,636	134.37	13	38,712,968	126.05
4	33,972,298	132.83	14	39,239,667	125.44
5	34,499,067	131.29	15	39,766,407	124.83
6	35,025,775	130.3	16	40,293,215	124.23
7	35,552,515	129.7	17	40,819,914	123.62
8	36,079,322	129.09	18	41,346,613	123.01
9	36,606,022	128.48	19	41,873,353	122.4
10	37,132,721	127.87	20	42,400,161	121.4

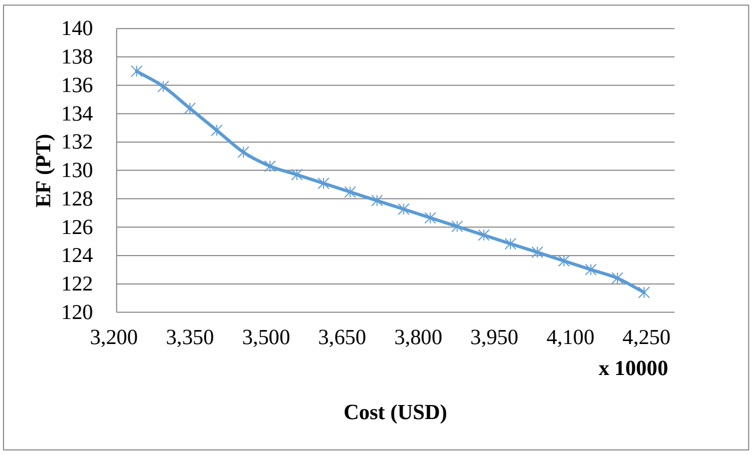

Figure 2. EF & Cost of Pareto frontier.

5.3. Discussion

Sustainable development goals have become a popular topic in the domain of sustainable development. Environmental footprint is a multi-objective problem. This study aimed to bridge the gap between theoretical and practical problems of environmental footprints. From Table 6, it could be concluded that most environmental impacts are from the "manufacturing stage", and most of the environmental impacts of the "manufacturing stage" are from the energy used. If the enterprise wants to reduce the environmental impacts, the core strategy is to reduce the energy usage. In addition, the normal constraint method should yield multiple Pareto-optimal solutions rather than a single solution. Many studies only consider evaluation of carbon emissions. However, in this study, the supplier's manufacturing capacity and location are also considered. To sum up, the method of Pareto optimization provides a group of solutions for the reference of the enterprise. The enterprise could select its suitable solution based on the enterprise strategy. In Figure 2, the solution is not easily identifiable for the enterprise since there is no obviously solution for the 20 points. It means the enterprise could decide how much they wanted to improve their environmental footprint. Compared with 20 points, points 1–6 represent a much more significant environmental footprint improvement.

6. Conclusions

Based on this research, supply chain managers can use the Pareto frontier to select materials and suppliers based on their environmental policies. Moreover, this calculation can be performed very quickly based on the supplier's capacity, showing that the PEF is a useful tool to help enterprises economically reduce their environmental impacts. This research could be a very useful tool for the manager to estimate his/her supply chain network design.

For sustainable development goal 12 (ensure sustainable consumption and production patterns), enterprises need to address the challenges linked to air, soil, and water pollution, as well as exposure to toxic chemicals, under the auspices of multilateral environmental agreements. In the past, many studies have examined carbon reduction in supply chain network design, but few have considered environmental footprint optimization. As an environmental footprint study, this research is one of the industry pioneers for supply chain network design. Compared to research on carbon emissions reduction [27,31,35–38], this study more widely considers environmental impact reduction.

In general, there are three different ways to reduce environmental impacts. The first is to change to a material with a lower environmental impact. The second is to reduce the environmental impact of the process, while the third is to design supply chain networks with lower environmental impact. As Kuo et al. [32] mentioned, proper optimization of the supply chain may decrease its emissions. In this research, we used the Pareto frontier approach to investigate bi-objective supply chain network design and obtain uniform non-dominated Pareto solutions, which is the main contribution of this research to previous literature related to the use of multi-objective models for low environmental impact supply chain network design. These results are consistent with other studies.

Although the proposed optimization model is a noteworthy contribution to the literature on low environmental impact network design, it has its limitations. First, the case used is very simple, as some issues of uncertainty and risk level are not considered. Second, it only considers the aspect of electricity. For future research, we suggest that researchers consider different levels of design criteria and examine a more sophisticated case.

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