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Abstract: Few studies on supply location decisions focus on enhancing triple bottom line (TBL) sustainability in supply chains; they rarely employ objective quantifiable measurements which help ensure consistent and transparent decisions or reveal relationships between business and environmental trade-off criteria. Therefore, we propose a decision-making approach for objectively selecting multi-tier supply locations based on cost and carbon dioxide equivalents (CO_2e) from manufacturing, logistics, and sustainability-assurance activities, including certificate implementation, sample-checking, living wage and social security payments, and factory visits. Existing studies and practices, logic models, activity-based costing, and feedback from an application and experts help develop the approach. The approach helps users in location decisions and long-term supply chain planning by revealing relationships among factors, TBL sustainability, and potential risks. This approach also helps users evaluate whether supplier prices are too low to create environmental and social compliance. Its application demonstrates potential and flexibility in revealing both lowest- and optimized-cost and CO_2e supply chains, under various contexts and constraints, for different markets. Very low cost/CO_2e supply chains have proximity between supply chain stages and clean manufacturing energy. Considering sustainability-assurance activities differentiates our approach from existing studies, as the activities significantly impact supply chain cost and CO_2e in low manufacturing unit scenarios.

Keywords: multi-tier supply chain planning; manufacturing location decisions; sourcing decisions; green supply network design; sustainable locations; global value chain analysis; sustainable supply chain management; carbon footprint; sustainable practices; responsible strategic management

1. Introduction

Making strategic decisions on where to source materials and manufacture products has become a difficult task, as products may have raw and intermediary materials from many different locations and be assembled in different places, near or far, from its customers and focal firms who govern product supply chains. As such, product supply chains can become complex and fragmented, leading to difficulty in sustainable supply chain management and visibility, two features necessary to ensure product quality and environmental/social compliance [1]. These relate to business, environmental, and social/socio-economic dimensions of sustainability, known as the Triple Bottom Line (TBL) [2]. Environmental and social issues often occur at manufacturing sites of sub-suppliers (including subcontractors and suppliers of suppliers) [3]. These issues lead to more studies towards multi-tier sustainable supply chain management involving several aspects such as managing suppliers and sub-suppliers, sourcing from low-risk countries and locations, governance structure, environmental performance improvement, and physical and institutional distance between focal firms and suppliers [3–8]. Moreover, some of these studies, as well as other studies on sustainable manufacturing, have mentioned positive impacts of physical and institutional proximity on sustainable practices for enhancing TBL sustainability due to, for example, short distances allowing for easy inspection and governance visits to suppliers, as well as effective local environment- and social-related laws [3,7–9]. This demonstrates that supply location decisions are important for sustainable supply chain management and sustainable practice implementation for sustainability enhancement. However, none pay attention to how to choose supply locations, configure supply networks, or compare performance of different multi-tier supply chains in order to ensure all three dimensions of TBL sustainability, as well as reputational risk avoidance at any supply stage.

Supply chain sustainability can be constrained by some location- and distance-dependent factors such as energy sources of electricity and geographical distance, which cannot be changed or significantly improved on by focal firms or their suppliers after a supply chain has been established. Therefore, multi-tier supply location decisions require considerations of factors involved in activities along product supply chains to fully drive TBL sustainability and avoid switching costs from future changes of supply locations. In this paper, the phrase 'supply location decisions' refers to the decisions of focal firms on where to source raw and intermediary materials and where to manufacture or assemble final products, rather than who manufactures the materials and products.

Existing studies on supply location decisions and network design, especially those with the simulation and modelling approaches that have been the tools for many studies on complex and multi-tier supply chains [5], pay little attention to third-tier suppliers and TBL sustainability. Most relevant existing studies consider only first-tier suppliers who produce final products, while recent studies have started to consider second-tier suppliers who supply materials to the first-tier suppliers, as shown in Table 1. The nine articles in Table 1 were selected by reading abstracts of all retrieved articles from the Scopus database with search terms relating to design or model and manufacturing or supplier locations.

Table 1. Comparison between this paper and recently published journal articles relating to supply location decision model and network design retrieved from the Scopus database.

Article	Criteria and Focus	What and Where	3rd-Tier Supplier	2nd-Tier Supplier	1st-Tier Supplier	Ware-House [1]	Market [2]	Re-Cycling
[10]	Minimize total costs and maximize effectiveness of suppliers' equipment	Automotive		x	x	x	x	
[11]	Minimize risks (time, reliability, inventory, cost)	N/A			x			
[12]	Order frequency and lead-time impacts on costs and supply chain design	Automotive, France		x	x	x	x	
[13]	Reduce vehicle fuel consumption and emissions	Natural honey			x	x	x	
[14]	Optimize supply chain total costs	Cartridge, India	x	x	x	x	x	x
[15]	Minimize operational and fixed costs with return and demand uncertainty	Electric appliance, China			x	x	x	
[16]	Minimize costs, and transportation and investment trade-offs	Biomass			x	x	x	
[17]	Optimize carbon emissions and costs (cap and trade policy)	Generated dataset			x	x	x	
[18]	Minimize outsourcing costs with allocation and services to customers	Automobile, Iran		x	x		x	
This paper	Minimize or optimize supply chain cost and gas emissions, considering sustainability-assurance activities	T-shirt, Europe, China, America	x	x	x	x	x	x [3]

[1] It can refer to a distribution center and includes headquarters; [2] Its location may be the same as the warehouse location; [3] Our approach allows users to consider a recycling location but our application does not include it.

Table 1 also shows that only two of the recently published studies on supply location decisions and network design consider environmental sustainability and none consider social sustainability. In addition to the studies in Table 1, other related studies [19–25] similarly show that few of them considered social sustainability. This is consistent with the results of the review article by Chen et al. [26], which stated that few studies have explicitly used sustainability criteria in making facility location decisions, as well as the review article by Brandenburg et al. [27], which stated that studies on quantitative models for sustainable supply chain management have neglected the social dimension. Although we found that the Dou and Sarkis [28] study incorporated TBL factors into their offshoring outsourcing decisions model, their model is based on subjective opinions from managers for pairwise comparisons among factors rather than on objective measured performance for comparing different locations and suppliers. Objective measurement criteria are important in order to avoid possible mistakes from any one individual's subjective opinions on interpretation, misperception, and inability to process and logically optimize a large amount of data [29]. Moreover, quantifiable criteria allow data to be measured directly and input into the model, to understand users' values, preferences, requirements, and/or objectives, and to objectively choose and evaluate systems/supply chains that match the user's objectives, especially with trade-off criteria [30]. Additionally, using objective and quantifiable measures helps avoid uncertainties from subjective judgements and imprecise data [31].

For the supply location decisions, an empirical study by one of the authors [9] shows that managers of focal firms usually compare and choose supply locations and suppliers by calculating landed costs of products based on supplier quotations, together with requirements of certificates, auditing reports, and/or supplier visits by the managers in order to ensure environmental and social compliance at the suppliers' factories. However, few of them ensure that the quoted product prices by suppliers are not too low to allow the suppliers to produce high-quality products with proper environmental and social compliance. Furthermore, industrial practitioners mainly focus on waste reduction and sustainable design, including using sustainable materials for improving environmental sustainability; they overlook greenhouse gas emissions from energy sources used in manufacturing and transportation that are considered proximity manufacturing benefits on environmental and social dimensions of sustainability [32]. It is also important to consider gas emissions from managers travelling from headquarters to visit factories for price and style discussion, operation control, product inspection, and environmental and social compliance assurance, as the managers usually travel by plane, a transportation mode that emits high carbon dioxide equivalents (CO_2e) [9], where CO_2e is calculated from greenhouse gas emissions. Therefore, we aim to develop a supply location decision-making (SLDM) approach for finding multi-tier supply locations enhancing TBL sustainability in product supply chains with objective and quantitative measures on supply chain activities which are especially related to location- and distance-dependent factors. The SLDM approach will help answer two research questions:

1. Which supply chain configurations deliver low cost and/or CO_2e for different markets?
2. Which supply chain factors, including potential risks, highly influence cost and CO_2e of these configurations?

This paper has three main contributions:

1. Our SLDM approach extends the knowledge on supply chain cost and CO_2e calculation by including sustainability assurance activities performed by both manufacturers and a focal firm, in addition to the manufacturing and logistics activities used in other studies.
2. This paper calls for attention to location- and distance-dependent factors from industrial practitioners and researchers for proper supply location decisions and network design and from governments and energy/logistics service providers for enhancing the factors towards TBL sustainability.
3. This paper makes practical contributions by proposing the SLDM approach with pragmatic validity applicable to a wide variety of users with different organizational contexts and preferences.

The structure of this paper is as follows: Section 2 shows how the SLDM approach is formulated, as well as diagrams of the ten-step SLDM approach, suggested factors and computational scopes, and pathways and interconnection of factors, cost, CO_2e, and TBL sustainability; Section 3 explains the ten steps of the SLDM approach in detail; Section 4 demonstrates the application of the SLDM approach in viscose t-shirt supply chains; and Section 5 draws conclusion, research contributions, limitations, and implications, as well as practical and social implications.

2. Formulation of the Supply Location Decision-Making Approach

The development of the SLDM approach is based on industrial problems and practices from an empirical study and working experience of one of the authors, and accumulated knowledge from existing studies on location decisions, supply chain network design, and cost and environmental modelling, as shown in Table 2.

Table 2. Formulation of the supply location decision-making approach based on various studies.

Sources	Features Developed in the Approach
Author's study [1]	Multi-tier, visibility, and governance focuses
Author's study [2,3]	The application purpose for either designing a new supply chain or evaluating existing supply chains
Author's study [3]	How to objectively make manufacturing decisions for different markets
[13,17,20,23,24]	Carbon dioxide (CO_2) or greenhouse gas (GHG) emissions as measurement criteria
[21,22]	Measurement criteria by both cost and CO_2/GHG emissions, considering energy and electricity emissions, production capacity, and material quantities
[20]	Considering all forms of input/output factors: solid, gas, and liquid, as well as energy
Author's study [4], [22,23]	Considering logistics activities besides manufacturing activities
Author's study [5]	Considering reverse logistics for sending used products to recycling factories
Author's study [6]	Considering sustainability assurance activities performed by manufacturers and firms
[23,24]	Considering emissions from different transportation and production technology
Author's study [7], [19,25]	Observing effects of agglomeration and proximity between supply chain stages
[33]	Exploratory data analysis
[10,14,34]	Scenario-based technique analysis
[10,35]	Pareto frontier analysis
[36]	Sensitivity analysis

Remarks: 1–7 show empirical evidences as follows: [1] Most companies highly control supply chains by nominating materials specifications and sometimes suppliers; [2] Most companies prefer long-term relationships with suppliers and have yearly supplier evaluation; [3] A company cannot make a decision whether to split production of the same products for different main markets; [4] A manager questioned whether ship transportation of distance-manufactured products was more environmentally friendly than truck transportation of proximity-manufactured products; [5] A few companies send used garments to be recycled locally and abroad; [6] Companies require sustainability auditing/certificate at factories, samples before running a production, as well as factory visits by their managers; [7] Managers preferred locations in proximity to suppliers and markets, depending on the product.

The empirical study gave the authors insights of supply chain decisions and operations from interviewing 16 supply chain, purchasing, and sustainability control managers on why and how they choose local, nearshoring, and offshoring supply locations, calculate landed costs, ensure high product quality and sustainability compliances, and operate businesses with their suppliers and customers. The empirical study helps develop differentiating features of the SLDM approach from other existing studies, shown in Table 2. Some results of the empirical study are published in Sirilertsuwan, Hjelmgren and Ekwall [9]. Moreover, the insights on studied subject help enhance this research's validity by aiding the authors in understanding what caused the research findings during interpretation and analysis [37].

The SLDM approach consists of ten steps shown in Figure 1, described in detail in Section 3. The approach adopts two widely used objective measures from existing studies for comparing all possible supply chain configurations: cost and CO_2e from normalized greenhouse gas emissions. The approach adopts multivariate graphical and non-graphical exploratory data analysis [33], such as cross tabulation, stacked column charts, and scatter plots, to reveal important factors, agglomeration and proximity between supply chain stages, and the lowest or optimized cost and CO_2e supply chains to be selected. In the scatter plots, cost and CO_2e trade-offs are visualized, and optimized cost and CO_2e supply chains are revealed on the Pareto frontier. This helps inform users (i.e., decision makers) how an improvement in cost may negatively affect CO_2e, and vice-versa, when making their decisions [35] regarding a preferred supply chain matching user's cost and CO_2e preferences and constraints for this research. Our approach focuses on finding a low-cost and CO_2e supply chain from visualization techniques of Pareto frontiers rather than mathematical methods; therefore, we do not show computational methods for multi-dimensional sets relating to Pareto optimization. However, readers can further learn about computational methods from the Lotov [35] book and the Perez Loaiza, Olivares-Benitez, Miranda Gonzalez, Guerrero Campanur and Martinez Flores [10] study. Scenario analysis, which is a tool for strategic analysis [34], is adopted to help users better understand the causality of events and critical uncertainties as risk factors impacting target outcomes: the lowest or optimized cost and CO_2e supply chains. The approach also adopts sensitivity analysis [36] to analyze robustness on how changes or imprecision of input factors potentially affect the outcomes. Both scenario and sensitivity analyses help decision making with long-term planning [38]. Additionally, sensitivity analysis has also been used as a validation procedure in some models to evaluate supply chain performance [31].

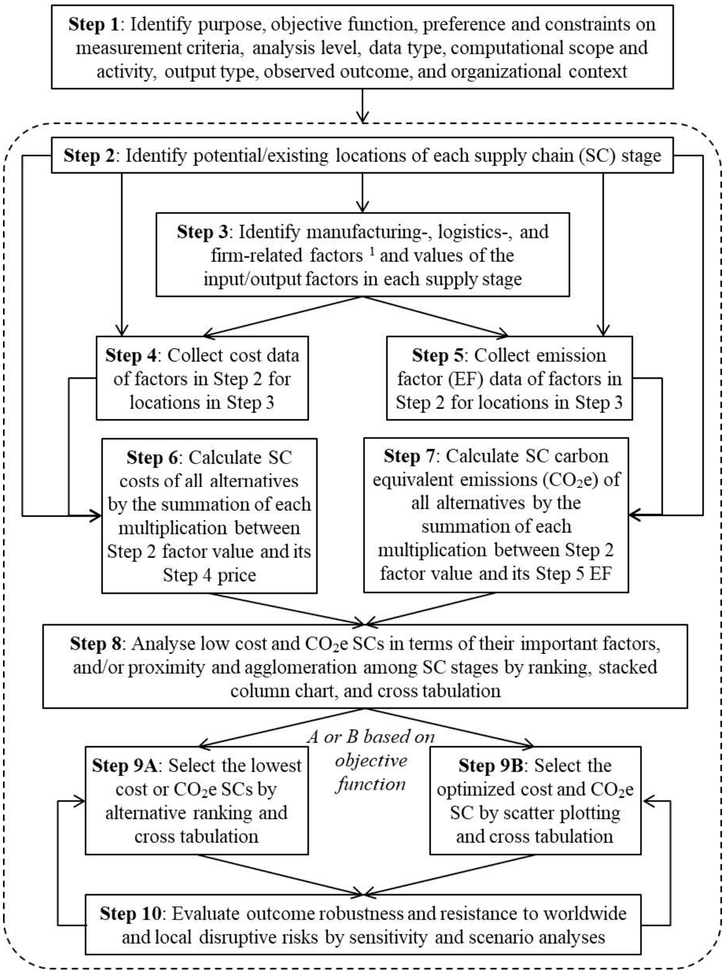

Figure 1. The ten-step supply location decision-making approach. Remarks: Data from Step 3 to Step 5 are stored in its matrix and linked to its coefficient matrix whose values vary during sensitivity and scenario analyses; [1] Suggested factors are shown in Figure 2.

Figure 2 presents a summary of the ten steps, supply chain stages, supply chain activities and their factors relating to manufacturing and remanufacturing, logistics and reverse-logistics, and focal firms for supply chain cost and CO_2e calculation. The factors and activities are from studies in

Table 2 and from authors after applying logic models and an activity-based costing (ABC) method in product supply chains. Logic models [39,40] are used as tools for identifying inputs, activities, outputs, and outcomes, as well as their pathways and interconnections shown in Figure 3, while ABC is used for allocating indirect costs and CO_2e to all manufactured units and is widely used in studies relating to supply chain decisions on organization performance, profitability, cost, productivity, and processes [41]. Furthermore, iteratively formulating and applying older versions of the approach into viscose t-shirt supply chains, as well as feedback from experts, also helps improve the lists of factors and the steps of the approach shown in Figure 2. We improved the approach by repeatedly comparing results with existing studies and theories to enhance validity. This process has been used in other studies to strengthen their findings [7]. Moreover, we also reflected what works in practice to produce intended outcomes for enhancing pragmatic validity [42].

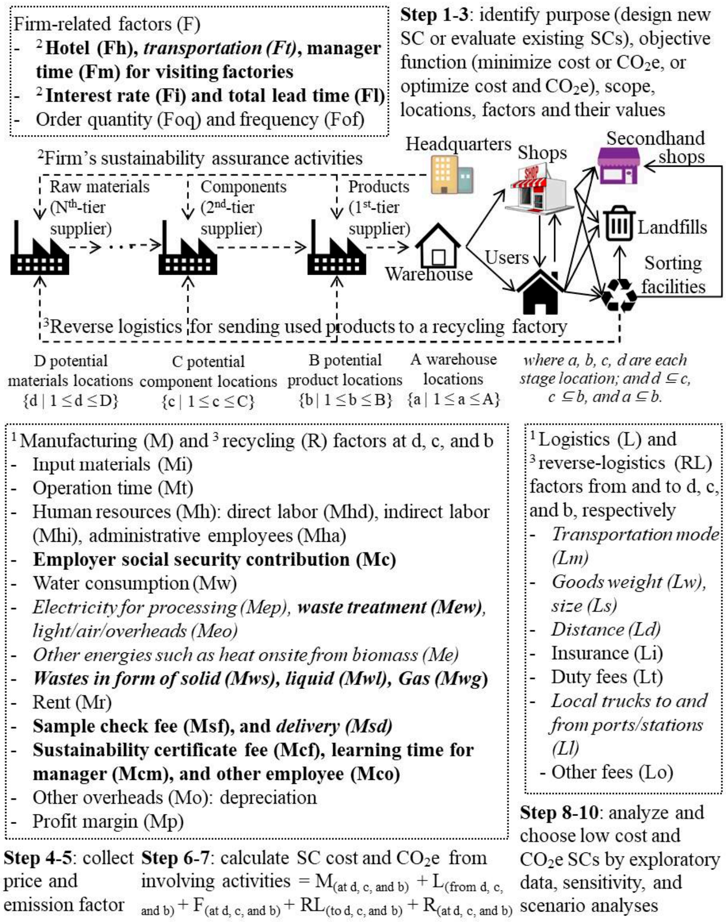

Figure 2. Factors, activities, and summarized steps in the proposed supply location decision-making approach with cost and carbon dioxide equivalent (CO_2e) criteria. Remarks: Bold factors are from sustainability assurance activities, differentiating this approach from traditional cost and/or CO_2e calculation; italicized factors involve CO_2e calculation; dashed arrows presents activities and supply chain stages whose cost and CO_2e are location- and distance-dependent for different supply locations; [1] for the landed scope; [2] added activities into the landed scope for the firm scope; [3] added activities into the landed or firm scope for the recycling scope.

In accordance with Figure 3, users who use the SLDM approach will understand which factors, from which activities performed by whom, influence which outcomes, aiding strategic supply chain planning and management. We consider cost and CO_2e outputs to be intermediate outcomes, and TBL sustainability to be a long-term outcome. The highlights in Figure 3 are how factors from sustainability assurance activities ultimately impact TBL sustainability, and how future socio-economic measurement criteria could be added.

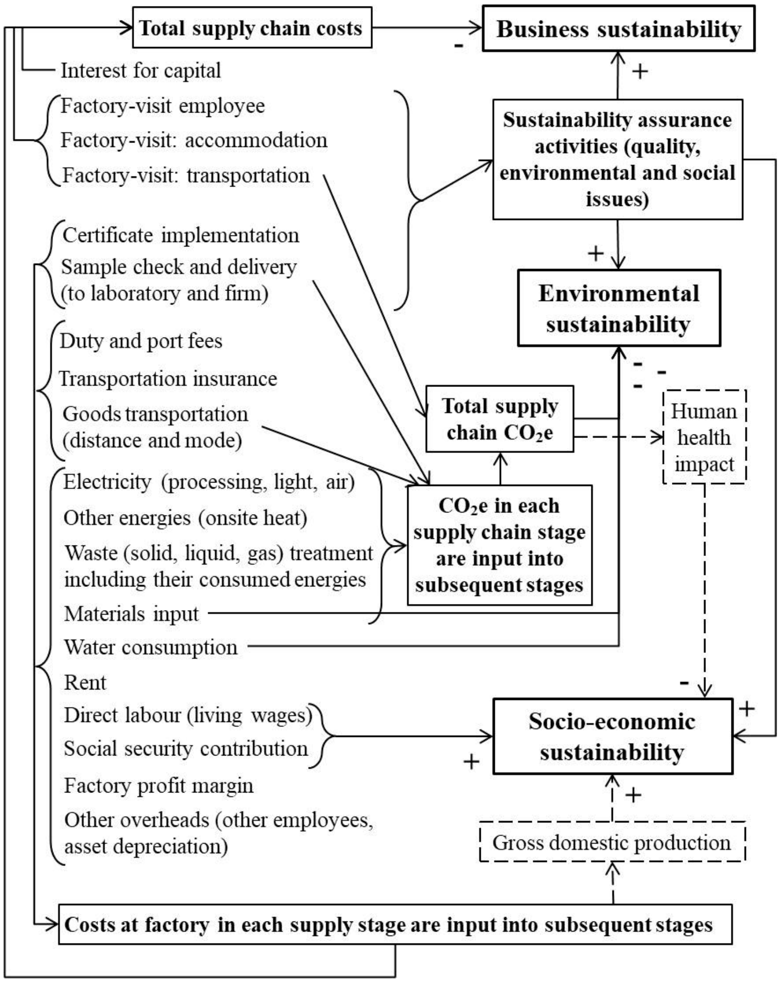

Figure 3. Pathways and interconnection among input and output factors from manufacturing, logistics, and firm's activities, cost and CO_2e measures, and the business, environmental, and socio-economic sustainability. Remarks: Dashed boxes and arrows present possible socio-economic measures for future research.

Our SLDM approach is normative in terms of required sustainability assurance activities performed by manufactures to ensure proper environmental and social compliance because minimum requirements for social and environmental standards at manufacturing sites can help sustainable supply chain management [43]. With our approach, focal firms can estimate prices of materials and products that are produced with sustainability assurance activities for TBL sustainability. If quoted prices by manufacturers are significantly lower than estimated prices, it is possible that the manufacturers cannot produce high product quality with good environmental and social compliance, as mentioned by managers from a prior empirical study performed by the author.

The SLDM approach has three cost and CO_2e computation scopes. The first is 'the landed scope,' which is similar to traditional landed cost and CO_2e calculation in terms of accumulating costs and CO_2e from suppliers to warehouse in a market. However, our landed scope includes sustainability assurance activities performed by manufacturers in the cost and CO_2e calculation, leading to differentiation from the traditional calculation. The activities relate to the bolded manufacturing and recycling factors in Figure 2. In addition to manufacturers, focal firms also perform sustainability-assurance activities, including visiting factories and paying interest to gain capital and cash flow for business operations.

Different manufacturing locations vary cost and CO_2e generated by these activities. Therefore, if focal firms perform these sustainability assurance activities, supply chain cost and CO_2e calculations have to include cost and CO_2e from these activities into the landed scope, hereafter referred to as 'the firm scope.' All sustainability assurance activities performed by both manufacturers and focal firms differentiate our SLDM approach from other studies and quantitative approaches for location decisions, as well as traditional cost and environmental computations. If products are recycled at one of the factories in any supply stage(s) after the consumer use phase, cost and CO_2e from sending used products back to the factory and from recycling processes will be included into the landed scope or the firm scope, to be referred to as 'the recycling scope.'

3. The Ten-Step Supply Location Decision-Making Approach

All ten steps of the SLDM approach in Figure 1 are explained below.

3.1. Step 1 to Step 3: Identification

Step 1 involves identifying all nine correlated aspects shown in Figure 4. These aspects help users identify what they want from and can do with the SLDM approach. Figure 4 shows flexibility and applicability of the approach to wide user groups. As shown in Figure 1 with the dashed frame, Step 1 is crucial for conducting the other steps of the SLDM approach to help align all steps and all possible supply chains to be comparable, ensuring validity.

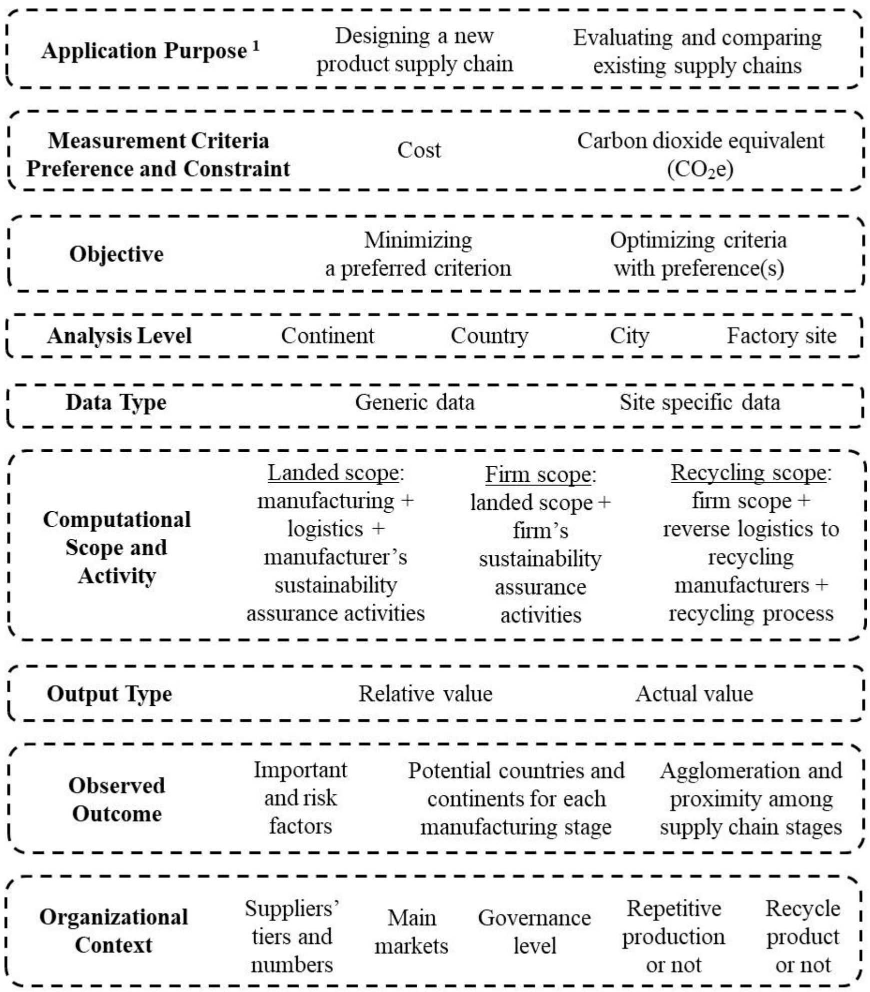

Figure 4. Aspects to be identified in Step 1. Remarks: [1] With specifying which product to be produced at which quantity per a production batch.

In order to generate all possible supply chains to be compared, Step 2 involves identifying potential or existing locations of each supplier in each supply stage depending on the application purpose. The sampled potential supply locations are based on a country's reputation on certain products, availability of suppliers and industrial setup, possible production capacity, and the proximity to natural resources, warehouses, and prior and subsequent supply stages.

As seen in Figure 4, supply chain cost and CO_2e of all possible supply chains to be compared can be either relative or actual total values, which influences Step 3. The relative values can fulfil the aim of the SLDM approach by focusing on location- and distance-dependent factors from activities generating different cost and CO_2e among different supply locations. Users can calculate relative values of cost and CO_2e based on the factors in Figure 2. On the other hand, the actual values can be calculated by including additional activities such as distribution, retailing, consumption, waste management, product design and development, and sales and marketing. Users can use logic models and ABC to reveal these factors. Amounts of manufacturing inputs and outputs, as well as distance and time for sample, product, and manager transportations, are gathered in Step 3. Data for these factors are stored in manufacturing-, logistics-, firm-, reverse logistics-, and recycling-data matrices, whose cells are multiplied with coefficient values from manufacturing-, logistics-, and firm-coefficient matrices. Every data matrix in Step 3 to Step 5 has its own coefficient matrix. The coefficients are beneficial to sensitivity and scenario analyses in Step 10 as they allow for easy changing of factor values and comparison, and are initially set to values of 1.

3.2. Step 4 and Step 5: Data Collection on Cost and Emission Factors

Cost and Emission factors (EFs) of the identified factors in Step 3 for each potential location in Step 2 are stored in cost and EF matrices whose cells are multiplied with coefficient values from their own cost- and EF-coefficient matrices. EFs of the main GHGs to be collected are CO_2, CH_4, and N_2O EFs, which can be found online, for example, on the websites of Greenhouse Gas Protocol [44] and The Intergovernmental Panel on Climate Change (IPCC) [45]. Users need to collect EFs for different locations from the same source for comparable results. The CO_2, CH_4, and N_2O EFs are normalized into the same unit, which is CO_2e, by multiplying the Global Warming Potential (GWP) by the CO_2, CH_4, and N_2O EFs, as shown in Equation (1).

$$CO_2e = ((EF_{CO2} \times GWP_{CO2}) + (EF_{CH4} \times GWP_{CH4}) + (EF_{N2O} \times GWP_{N2O})) \quad (1)$$

where GWP_{CO2}, GWP_{CH4}, and GWP_{N2O} from the IPCC fifth assessment report are 1, 28, and 265, respectively.

3.3. Step 6 and Step 7: Supply Chain Cost and CO_2e Computation

Each of the possible supply chains has its supply chain cost or CO_2e of producing one-batch products by summing all factor costs from all activities within the identified computational scope in Step 1. CO_2e computation involves the italicized factors shown in Figure 2. Based on the identified scope, activities, and the number of supply stages and suppliers in each stage, supply chain cost and CO_2e of the three scopes can be calculated by Equation (2).

$$\textit{Supply chain cost or CO2e} = \sum_{i=1}^{N} \sum_{j=1}^{S} \left(CM_{ij} + CL_{ij} + CF_{ij} + CRL_{ij} + CR_{ij} \right) \quad (2)$$

where i represents each supply stage of N, the total number of supply stages; j represents each supplier in each supply stage, and S is the maximum number of the total number of required suppliers in each i^{th} supply stage; CM, CL, CF, CRL, and CR are accumulated costs or CO_2e of factors from activities relating to manufacturing (CM) at a factory, logistics (CL) from a factory, firms' sustainability assurance (CF) involving a factory, reverse-logistics (CRL) to a factory, and recycling process (CR).

Each factor cost or CO_2e from the activities is calculated by multiplying its factor value from Step 3 with its cost rate from Step 4, or its normalized CO_2, CH_4, and N_2O EFs from Step 5. Indirect and fixed costs or CO_2e are allocated into a production batch using ABC. Time-based costs are allocated by using factory operating time per day and per month, rather than 24 h and 30 days, respectively.

3.4. Step 8: Supply Chain Analysis on Important Factors and Proximity among Stages

This step adopts exploratory data analysis to reveal important factors influencing supply chain costs and CO_2e, as well as which supply chain stages should be agglomerated or be in proximity to each other in order to achieve very low cost and CO_2e supply chains, and ultimately what those locations are. Therefore, the SLDM approach helps users not only with supply location decisions, but also with supply chain planning on possible future disruptions and investing resources to find and establish relationships with proper suppliers from the locations that generate very low cost and CO_2e. Agglomeration between supply stages in the approach refers to either two suppliers for subsequent supply stages located in the same area (resembling business clusters), or one supplier performing manufacturing of two supply stages (resembling vertical integration).

All possible supply chains are ranked by cost and CO_2e from the lowest to the highest values. Users choose a set of supply chains to be analyzed based on their cost and CO_2e preferences, as well as any constraints. After that, stacked column charts of the supply chains are plotted to reveal important factors influencing total costs and CO_2e. Cross-tabulation of agglomeration or proximity between two supply chain stages and their common countries or continents shows which supply chain stages should be agglomerated or located in proximity in order to achieve supply chains with preferred cost and CO_2e. Cross-tabulation can also be used to compare results of different markets and computational scopes in order to find their common supply chains. Comparing results of different computational scopes also aids users in seeing the feasibility of adopting a firm's sustainability assurance and recycling activities.

3.5. Step 9: Supply Chain Selection Based on an Objective Function

As shown in Figure 1, Step 9 has options A and B. Option A is for selecting a supply chain with the lowest cost or the lowest CO_2e that are known from supply chain cost and CO_2e rankings in Step 8, while Option B is for selecting an optimized low-cost and CO_2e supply chain by scatter plotting. The scatter plot between cost and CO_2e of all alternatives reveals a Pareto frontier containing optimized low cost and CO_2e supply chains, which represents cost and CO_2e trade-off solutions for conflicting multi-criteria [35]. The optimized supply chains on the Pareto frontier can be found automatically by coding Pareto computational methods into a program. Alternatively, optimized supply chains can be found manually by identifying the supply chain with the lowest value of a selected criterion on either the x-axis or y-axis, and then identifying the next optimized supply chain with the next lowest value of the same criterion from supply chains located between the previously identified supply chain and zero in the scatter plot. Repeat this until reaching the supply chain with the lowest value of the other criterion. Users can choose a final supply chain based on their cost and CO_2e preferences and constraints. Users can also choose a set of optimized supply chains to look for suppliers and then use other criteria to choose a final supply chain, such as relatively superior knowledge and technology, optimal collaboration or existing relationships with suppliers, government support and trade policies, and political situations of manufacturing areas. As shown in Figure 1, results of sensitivity and scenario analyses in Step 10 will serve as feedback to this step to help in choosing a supply chain which has high resistance to risk and changing environments. Additionally, different markets may have common and different optimized supply chains which can be revealed by cross-tabulation.

3.6. Step 10: Evaluation on Outcome Robustness and Resistance to Risks

This step evaluates the robustness and resistance to risk of outcomes and the selected supply chains by sensitivity and scenario analyses. Various what-if situations are generated by changing coefficients of each factor value possibly affecting supply chains. This helps users foresee risk impact on supply chain/location attractiveness and competitiveness [38] in terms of cost and CO_2e.

Sensitivity analysis is performed by changing coefficients of each factor value in either all locations at once, or each location at a time, to imitate global and local disruptions, respectively. The results of the sensitivity analysis help users recognize important factors, including risk factors, which make the selected supply chains in Step 9 less competitive. Risk factors are those for which small changes in factor coefficients cause the selected supply chain to lose its cost and CO_2e competitiveness or to violate the user's cost or CO_2e preferences and constraints.

Scenario analysis is performed by changing a coefficient of a factor at different levels to represent different scenarios of possible future problems which arise from current situations, such as trade wars, and from important factors revealed in Step 8 and in this step by the sensitivity analysis. Common results of different scenarios should be chosen because they have high resistance to changing environments that help avoid the switching costs of changing suppliers for new supply chains in the future and ensure smooth operations [46].

4. Application for Selecting Supply Locations of Viscose T-Shirts

We choose to apply our proposed approach in the textile and clothing industry, as we have expertise and insights into the industry, benefiting the application. Viscose t-shirts were selected due to the possibility to generate several possible supply chains and scenarios. T-shirts are a basic product without specialized manufacturing-skill requirements, affording a high degree of flexibility in finding various potential manufacturing locations in proximity to or far from warehouse and materials supply locations. Together with worldwide viscose fiber production with controlled quality due to man-made materials, viscose t-shirts can have several comparable possible supply chain configurations. Regarding several possible scenarios, t-shirts allow both repetitive and non-repetitive production scenarios because t-shirts are basic products that usually have continuous demand, except for some styles and materials with low sales. Of note, details of calculation, data inputs, and results are shown in the Appendix A–C.

4.1. Step1: Identification of Core Aspects

We identify core aspects shown in Figure 4. The purpose of this application is to design a new supply chain for producing 1800 t-shirts to serve the main market in Europe with consideration of future markets in US and China. We assume that headquarters and a warehouse of the focal firm are at the same location in Germany because it is the main market for the European clothing industry [47]. The objective is to optimize cost and CO_2e within the 10,000-euro budget and with the least possible CO_2e. Analysis levels for proximity and agglomeration between supply chain stages are at the country and continent levels. Due to a new supply chain, there are no specific and previous data from suppliers to be collected. Therefore, all collected data are generic and publicly available at the country or city level. The computational scope is the firm scope based on industrial practices of visiting factories regularly and rarely having in-house recycling programs. Additionally, headquarters have in-house garment design with nominated materials and suppliers, and as such, suppliers must send samples to headquarters and laboratories for quality assurance. The computational outputs are relative values of supply chain cost and CO_2e. Regarding organizational contexts, there are three supply stages with one major supplier in each stage. As mentioned before, as viscose t-shirts have the possibility of low sales, the cost and CO_2e computation will start with a one-batch scenario followed by six-, twelve-, and eighteen-batch scenarios for one-, two-, and three-year sales of the same product, respectively. We will observe important factors, potential locations of each supply stage, and proximity and agglomeration among supply chain stages.

4.2. Step 2: Location Identification

Starting with fiber production locations, we assumed six potential locations of fiber manufacturing based on manufacturing locations of the Lenzing Company, which uses environmentally friendly manufacturing technology. Fabric and garment manufacturing have the same potential locations as fiber manufacturing and warehouse and headquarters in Germany, as shown in Figure 5. The other potential fabric and garment manufacturing locations are selected due to country reputation and availability of viscose fabric and t-shirt manufacturing from online searches. To observe the effects of local, nearshoring, and offshoring manufacturing to supply chain cost and CO_2e, we sampled the locations based on cost and distance to Germany. In total, there are 1536 potential supply chain configurations from 6 fiber manufacturing locations, 16 fabric manufacturing locations, and 16 garment manufacturing locations.

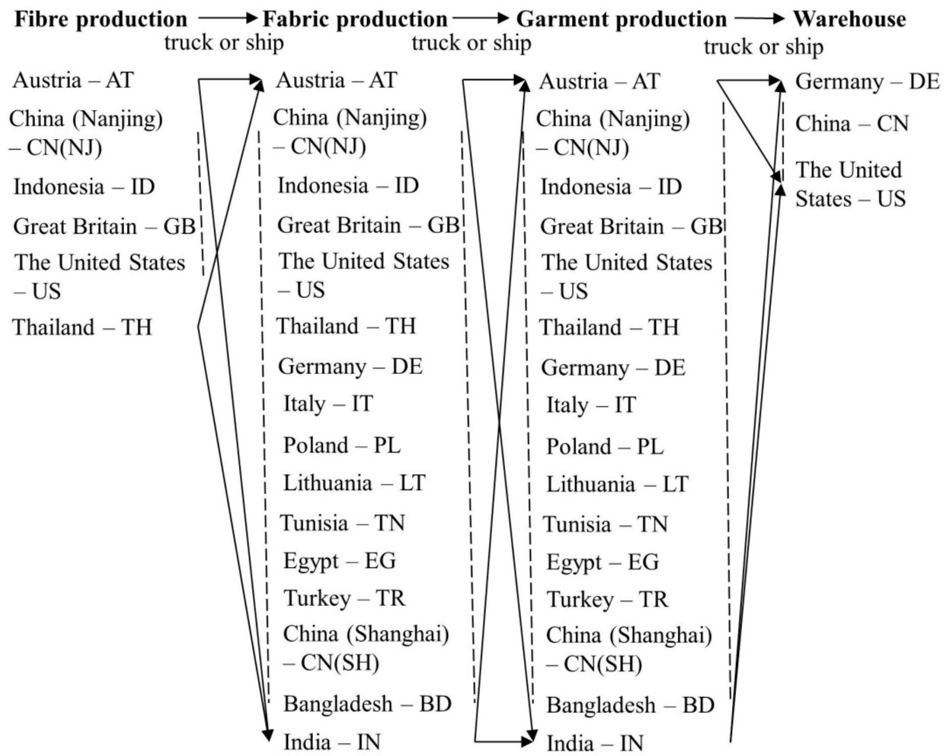

Figure 5. Potential manufacturing locations and their acronyms for each supply stage of t-shirt supply chains.

Hereafter, acronyms of locations in Figure 5 will be used when mentioning three-tier supply locations of a supply chain. For example, AT-EG-LT refers to fiber manufacturing in Austria, fabric manufacturing in Egypt, and garment manufacturing in Lithuania.

4.3. Step 3: Factor and Their Value Identification

In accordance with the firm scope identified in Step 1, we considered factors shown in Figure 2, from fiber, fabric, to garment manufacturing stages. Fabric manufacturing includes thread spinning, knitting, and dyeing. Garment manufacturing includes cutting and sewing. The inputs and outputs of each process are calculated based on inventory data in the Angelstam, et al. [48] study by starting with 360 kg of 1800 t-shirts. This allows us to find the transported weights of fabrics and fibers, which are 442.64 and 540.02 kg, respectively. The fiber quantity is used for finding energy use in fiber manufacturing based on the Shen and Patel [49] study. Fabric dyeing and cutting machine capacities are based on studies of Amin [50] and Phakphonhamin and Chudokmai [51]. Operation time is assumed to be 6.48 min per t-shirt [52].

Based on Step 2, only Austrian fiber manufacturing uses the environmentally friendly manufacturing technology, which provides much lower amounts of non-renewable energy use (NREU) than the normal technology in the other locations. We also consider cost and CO_2e from electricity used in wastewater treatment that are calculated based on the study of Yin et al. [53]. Distance and delivery time between locations for assigned transportation mode are obtained from Searates.com, a logistics provider's website. Trucking is used for domestic transportation in China and between factories and ports for international transportation by ship, as well as international transportation between Germany, Italy, Poland, and Lithuania. International transportation between the other locations uses shipping. More manufacturing data are in Tables A1–A8 in Appendix A.

4.4. Step 4 and Step 5: Data Collection of Cost and Emission Factors

We searched for the costs of factors related to Figure 2 online in 2019. Costs of employees to train themselves and write reports for the certificate and auditing, as well as costs of managers to visit factories, are calculated based on employees' time spent on the activities; the costs are allocated into one-batch production using ABC, based on the number of years that the certificate is valid, factory working time for one-batch production, and the number of manufacturing batches before a new factory visit by a manager from headquarters. Cost data in details are in Tables A9–A22 in Appendix A.

Electricity EFs of each country are obtained from emissions per kWh of electricity consumed shown in the Brander et al. [54] technical paper. EFs of NREU, renewable energy use (REU), landfill gas, good transportation by truck and ship, and passenger car for domestic travelling of managers to visit factories are from an excel sheet provided by Greenhouse Gas Protocol [44]. Without using EFs for CO_2e calculation, kgCO_2e of sample delivery and flights for a manager to visit factories are from the DHL carbon calculator on its website, as well as from the flight search function of the FlyGreen website [55].

4.5. Step 6 and Step 7: Supply Chain Cost and CO_2e Computation

We multiplied factor values from Step 3 by cost rates and EFs from Steps 4 and 5, respectively, to get costs and CO_2e from manufacturing, logistics, and firm activities involved in each supply stage. Detailed calculation of these costs and CO_2e is shown in Appendix B. After that, the costs and CO_2e are input into Equation (2) to compute supply chain costs and CO_2e of all 1536 possible supply chains for the European market. As we stated in Step 1 regarding the future markets in China and US, we also calculated another two sets of costs and CO_2e of 1536 possible supply chains for the Chinese and US markets. Selected results of the three markets are shown in the next steps.

4.6. Step 8: Supply Chain Analysis

In this step, we focus on only the current market in Europe; therefore, we ranked all 1536 possible supply chains of the European market from the lowest to the highest values of cost and CO_2e. After that, we select the 1% lowest-value supply chains, as shown in Table A23 in Appendix C, to analyze important factors as well as potential locations and proximity among supply chain stages.

Stacked column charts are used to break down costs and CO_2e from all activities along each supply chain to reveal which factors significantly influence the supply chain costs and CO_2e, as shown in Figures A1 and A2 in Appendix C. Cost of visiting factories (in terms of a manager's compensation) is the greatest influence of the supply chain cost, followed by fiber price, fiber transport, transportation cost of visiting factories, and fabric overhead of administrative employees, including manager and their social security contribution. The high costs of manager compensation and transportation to visit factories can be reduced by repetitive manufacturing before a new factory visit. The effects of repetitive manufacturing on costs and CO_2e will be shown in Step 10 during the scenario analysis on different numbers of manufacturing batches. Of note, the 1% lowest-cost supply chains have agglomerated fabric and t-shirt manufacturing locations in Egypt, Tunisia, Turkey, and Poland, which are relatively lower cost countries located in proximity to warehouse and headquarters in Germany. The results highlight that paying relatively high transportation cost of materials to have components and product manufacturing in a relatively low cost country located in proximity to the market helps achieve very low cost supply chains. This contributes to the Weber [25] theory by adding international location aspects with different manufacturing costs and three supply stages.

The stacked column chart of the 1% lowest-CO_2e supply chains shows that fiber REU significantly influences the firm-scope CO_2e of the 16 lowest CO_2e supply chains, followed by fiber NREU. The results highlight the importance of environmentally friendly technology in fiber manufacturing to achieve very low CO_2e. All 16 lowest CO_2e supply chains have fiber manufacturing in Austria, the only location with environmentally friendly technology. Electricity EFs and proximity to Germany, implying lower transportation emissions, are important factors to fabric and garment manufacturing locations of very low CO_2e supply chains. This is evidenced by the fact that half of the 16 lowest CO_2e supply chains have fabric and garment manufacturing in Germany rather than America, Thailand, and Bangladesh, whose electricity EFs are smaller than Germany's. The CO_2e stacked column chart also demonstrates that transportation CO_2e rates are much lower than manufacturing CO_2e rates. This calls for attention to proper interpretations on the reduction of GHG emissions in some countries, such as high reduction of European industrial GHG emissions [56]. The reduction can be from migrating European industries and industrial emissions to other relatively lower cost countries rather than effective policies, infrastructure, and technology to reduce world CO_2e. Therefore, consumption-based accounting is a good alternative for calculation carbon dioxide emissions [57]. Moreover, manufacturing products for European consumers in other countries possibly increases total GHG emissions due to longer transportation and unclean sources of energy.

Agglomeration and proximity analyses on the 16 lowest cost and CO_2e supply chains are shown in Table 3. Fabric and garment manufacturing locations in the same countries, especially in Tunisia and Egypt, show high possibilities to achieve very low cost supply chains, while proximity among all supply chain stages in Europe helps achieve very low CO_2e supply chains.

Table 3. Cross-tabulation results of proximity and agglomeration between supply chain stages from the 16 lowest cost and CO_2e supply chains.

Proximity or Agglomerated Stages	Cost, Country	Cost, Continent	CO_2e, Country	CO_2e, Continent
Fiber and fabric		EU (1)	AT (5)	EU (16)
Fabric and garment	PL (2), TN (6), EG (6), TR (2)	EU (4), AF (12)	AT (1), DE (1), IT (1)	EU (16)
Garment and warehouse		EU (4)	DE (4)	EU (16)
Fabric and firm		EU (4)	DE (5)	EU (16)
Garment and firm		EU (4)	DE (4)	EU (16)

Remarks: Number in parenthesis refers to the number of supply chains out of the 16 lowest cost and carbon dioxide equivalent (CO_2e) supply chains which have location proximity and agglomeration between stages; EU refers to Europe and other acronyms refer to Figure 5.

4.7. Step 9: Supply Chain Selection

Based on the objective, we plot all 1536 supply chains in a scatter plot between cost and CO_2e to find optimized cost and CO_2e supply chains which are located on its Pareto frontier line, as shown in Figure A3 in Appendix C. The results show ten optimized supply chains, six of which have costs within the budget. Ultimately, we selected Poland and Austria for t-shirt/fabric production and fiber sourcing, respectively (AT-PL-PL), because this supply chain has the lowest CO_2e. Of note, five of the ten optimized supply chains have fiber, fabric, and garment manufacturing in Europe, while the other five supply chains have fabric and garment manufacturing in Africa with Austrian, US, and Indonesian fibers. This shows that the supply locations of the optimized supply chains are similar to the locations of very low cost and CO_2e supply chains in terms of the proximity between fabric and garment manufacturing, and that their locations are in proximity to Germany.

To ensure the selected supply chain can serve the future markets in China and America, we use cross-tabulation among Pareto-optimized supply chains of all three markets, as shown in Table 4. Table 4 shows that the selected AT-PL-PL supply chain exceeds the 10,000-euro budget when producing 1800 t-shirts to be delivered to the Chinese and US markets. Therefore, we select a new supply chain that uses Austrian fibers to produce fabrics and t-shirts in Egypt (AT-EG-EG) because this represents the lowest CO_2e optimized supply chain within budget.

Table 4. Pareto-optimized supply chains of three markets with costs and carbon dioxide equivalent (CO_2e) for one 1800-t-shirt batch.

Supply Chain	DE, €	DE, kg CO_2e	CN, €	CN, kg CO_2e	US, €	US, kg CO_2e
AT-AT-AT	15,867	6122	20,494	6256	18,827	6288
AT-AT-LT	15,387	6438	19,010	6487	17,928	6596
AT-IT-IT	13,392	6548	17,313	6641	15,929	6694
AT-LT-LT	10,325	6616	13,176	6665	12,377	6774
AT-PL-PL	8685	7791	11,233	7882	10,540	7990
AT-TR-TR	-	-	10,989	8102	10,048	8119
AT-TN-TN	8572	8056	10,088	8133	9425	8177
AT-EG-EG	8215	8291	9871	8368	9030	8370
US-TN-TN	7921	10041	9253	10,117	8660	10162
ID-EG-EG	7777	10245	-	-	8515	10324
US-EG-EG	7768	10296	-	-	8505	10375

Remarks: Supply chain name refers to its fiber-fabric-garment manufacturing locations; acronyms of locations refer to Figure 5.

4.8. Step 10: Supply Chain Evaluation by Sensitivity and Scenario Analyses

We perform sensitivity analysis as a validation procedure [31]. The application outcomes in terms of the lowest cost and CO_2e supply chains are robust when increasing or decreasing coefficient values of the following manufacturing factors by 25 percent: productivity, solid waste amounts, percentages of profits and factory overheads, and interest rates.

When changing coefficients of each cost factor in all locations or one location at a time by 25 percent, the lowest cost supply chain (US-EG-EG) is affected by changing values of fiber prices and transportation costs. The results show that fabric and garment manufacturing in Egypt will still be the best alternative location for achieving the lowest cost supply chain, but fibers would have to be sourced from Indonesia instead of America. Other fiber manufacturing locations aside from Great Britain will be fiber locations of the new lowest cost supply chain if their prices decrease. Furthermore, Tunisia will become the fabric and garment manufacturing location instead of Egypt after decreasing Tunisian operator wages, ship freight to Tunisia, or manager and transportation costs to visit factories in Tunisia, or after increasing ship freight to Egypt or manager and transportation costs to visit Egypt. Changes of the following factors do not change the lowest cost supply chain: truck fees, duty fees of fibers, fabrics, and garments from and to every location, indirect labor wages, wood prices for onsite energy, electricity fees, rent, solid waste management fees, certificate fees and implementation, sample delivery, lab test fees, and hotel costs during factory visits.

When changing coefficients of each CO_2e factor at all locations or one location at a time, only increasing CO_2e of factory-visiting flights to Austria or all locations at once changes the lowest CO_2e supply chain to have fabric and garment manufacturing in Germany instead of Austria. The lowest CO_2e supply chain remains the same after changing values of the following factors by 25 percent: CO_2, CH_4, and N_2O EFs of NRUE, REU, solid waste landfill, truck vehicle, and ship vessels, and CO_2e of sample delivery.

To see whether the selected optimized supply chain (AT-EG-EG) has high resistance to changing environments, we changed the coefficients of each manufacturing and cost factor relating to Austrian and Egyptian manufacturing, logistics, and sustainability assurance activities until the firm-scope cost of the supply chain exceeded the 10,000-euro budget. The results are in Table 5 and show that the selected supply chain has high resistance to all of the factor changes.

Table 5. Resistance of the selected supply chain to changes of factor values by changing their coefficients until the supply chain cost exceed the 10,000-euro budget.

Manufacturing Consumption Rate Coefficient	New Coefficient	Percent Change
Fabric factory productivity (working time)	0.28	−72.36
Garment factory productivity (working time)	0.12	−88.19
Percentage of fabric factory overheads or profits	6.51	550.56
Percentage of garment factory overheads or profits	5.71	471.09
Interest rate for headquarter (DE)	40.03	3903.29
Fiber cost from Austria	1.98	97.73
Helper/cleaner wage	11.80	1080.14
Operator wage	4.32	332.29
Manager wage	4.06	305.81
Other administrative employee wage	152.77	15,177.00
Social security employer contribution	7.66	666.49
Electricity rate	19.45	1845.28
Woodchip price	131.15	13,014.59
Water rate	55.63	5463.49
Solid waste management fee	1225.64	122,464.42
Rent	5712.41	571,141.14
Fabric employee certificate costs	63.02	6202.14
Garment employee certificate costs	136.47	13,547.09
Fabric lab test fee	20.65	1965.17
Fabric sample delivery cost	107.02	10,601.84
Garment sample delivery cost	236.87	23,587.39
Transportation cost for visiting a factory	3.50	249.74
Manager cost for visiting a factory	1.64	64.04
Hotel cost for visiting a factory	41.32	4032.46
Ship LCL (Less-than-Container-Load) price from Austria and to Egypt	3.68	268.01
Ship LCL price from Egypt	4.94	393.93

Remarks: Original coefficient values are 1; the selected supply chain has fiber manufacturing in Austria and fabric and garment manufacturing in Egypt; Cost factors from helper/cleaner wage to hotel cost for visiting fabric and garment factories relate to only Egypt; and duty fees of fibers, fabrics, and garments between Egypt and European countries are zero so changing coefficients of duty fees does not affect anything.

As mentioned in Step 8, different scenarios will be created by varying the number of manufacturing batches to see their effects on supply chain costs and CO_2e. Scatter plotting in Step 9B is used to find optimized supply chains of 6-, 12-, and 18-manufacturing batches that are compared by cross-tabulation as shown in Table 6. High numbers of manufacturing batches allow costs of sustainability assurance activities to be allocated into several product units across the number of manufacturing batches leading to lower costs per batch. Table 6 shows that after increasing the number of batches to a certain level, per-batch cost and CO_2e do not decrease significantly. Cost and CO_2e of one-batch manufacturing are much higher than those of 6-, 12-, and 18-batch manufacturing. This demonstrates the importance of calculating cost and CO_2e from sustainability assurance activities for products with low numbers of manufacturing units and batches per factory visit. Table 6 also shows that the more manufacturing batches, the more Pareto-optimized supply chains exist. There are six common optimized supply chains among 1-, 6-, 12-, and 18-manufacturing batches, and three of them have costs within budget. Out of the three, AT-EG-EG is the only one applicable to all three markets. This step confirms that the selected supply chain (AT-EG-EG) has high resistance to different markets and number of manufacturing batches.

Table 6. Costs and carbon dioxide equivalent (CO_2e) per one 1800-t-shirt batch for Pareto-optimized supply chains of 6-, 12-, and 18-manufacturing batches for the European market.

	1 Batch		6 Batches		12 Batches		18 Batches	
Supply Chain	**€**	**kg CO_2e**	**€**	**kg CO_2e**	**€**	**kg CO_2e**	**€**	**kg CO_2e**
AT-AT-AT	15,867	6122	13,769	5527	13,559	5467	13,489	5447
AT-AT-LT	15,387	6438	10,953	5695	10,509	5621	10,361	5596
AT-IT-IT	13,392	6548						
AT-LT-LT	10,325	6616	7893	5725	7650	5636	7569	5606
AT-PL-PL	8685	7791						
AT-TN-LT			7508	6114	6956	5989	6772	5948
AT-EG-LT			7388	6139	6849	6002	6669	5956
AT-TN-TN	8572	8056						
AT-EG-EG	8215	8291	5163	6448	4858	6264	4756	6203
US-TN-TN	7921	10,041						
AT-BD-BD					4811	6971	4673	6826
[1] ID-EG-EG	7777	10,245	4725	8403	4420	8218	4318	8157
[1] US-EG-EG	7768	10,296	4716	8454	4411	8270	4309	8209
ID-BD-BD					4374	8658	4235	8513
CN(N)-BD-BD					4357	8736	4218	8590
ID-ID-ID					4347	8820	4206	8620

Remarks: These supply chains with different values are also Pareto-optimized supply chains of the Chinese and United States markets unless stated; [1] they are not Pareto-optimized supply chains for the Chinese market; and acronyms of locations refer to Figure 5.

5. Conclusions, Contributions, Limitations, and Implications

This paper proposes a strategic supply location decision-making (SLDM) approach for systematically analyzing and selecting multi-tier supply locations of a product supply chain, taking into consideration triple bottom line (TBL) sustainability and resistance to risk and changing environments. Its development is based on industrial practices and problems as well as literature relating to supply location decisions and network design, and cost and carbon dioxide equivalents (CO_2e) modelling. Adopting key aspects from existing studies and expert opinions, as well as iteratively developing and applying the previous version of the approach in product supply chains, helps improve the SLDM approach and increase its validity and reliability. Following the ten steps of the approach for application in the viscose t-shirt supply chain allows us to find, within specified cost constraints, the lowest and optimized cost and CO_2e supply chains for two different scenarios: first, with one supply chain that supplies all markets; and second, with separate supply chains for each market. Sensitivity and scenario analyses demonstrate the approach's capability in delivering robust and high-resistance outcomes to changing factor values and environments.

The application reveals that agglomerated fabric and garment manufacturing located in a relatively low-cost country in Africa in proximity to a German warehouse and headquarter helps achieve very low cost supply chains, while proximity among fiber, fabric, and garment manufacturing located in European countries, whose emission factors of consumed energy and electricity are low, helps achieve very low CO_2e supply chains. Fiber manufacturing technology highly influences supply chain CO_2e while sustainability-assurance activities performed by focal firms highly influence supply chain costs especially of products with a low ratio of production units per factory visit by the focal firm. The application shows the potential and pragmatic validity of the approach for aiding users to choose a supply chain configuration which enhances positive impact and attempts to reduce negative impact on each TBL dimension of sustainability, based on users' cost and CO_2e constraints and preferences, as well as organizational contexts.

5.1. Research Contributions

The application results show that the approach can deliver answers to both research questions on finding the lowest or optimized low cost and CO_2e supply chains for different markets and their important cost and CO_2e factors, including potential risks. By considering cost and CO_2e from sustainability assurance activities that are overlooked by existing studies which calculated cost and CO_2e in supply chains, our approach differentiates itself from the other cost and CO_2e computation methods in the existing studies. Moreover, its application reveals that supply locations of the lowest cost and CO_2e supply chains are not the lowest wage location and the market for zero transportation CO_2e. This is because reduced costs of transportation, duty, and factory visits from geographical proximity between fabric and garment manufacturing locations and headquarters outweigh reduced labor costs at factories. Furthermore, sources of energy and electricity for manufacturing activities have more influence on supply chain CO_2e than transportation activities. As such, this research contributes to the following:

1. Supply location and manufacturing decision literature and quantitative decision-making approaches, by proposing a comprehensive supply location decision-making approach with manageable numbers of objective measurement criteria that integrate cost and CO_2e from all business, environmental, and socio-economic factors of sustainability, as there is a need to integrate environmental and social aspects into criteria of sustainable supplier selection with solvable problems [27].
2. Computations of cost and CO_2e in supply chains for the purpose of comparing supply chains, locations, and products, by considering cost and CO_2e from sustainability assurance activities performed by focal firms. These activities have significant influence on supply chain cost and CO_2e, especially for products requiring high degrees of control by the focal firms.
3. Sustainable supply chain management literature, by helping identify which cost and CO_2e factors most significantly influence supply chain cost and CO_2e. Moreover, readers can identify which of the factors are location- or distance-dependent and thus cannot be improved by manufacturers and focal firms, implying limits to supply chain performance improvements. Manufactures and focal firms will have to rely on other stakeholders, such as governments and logistics providers, to improve the cost and CO_2e factors by means such as implementing clean sources of electricity and transportation technology to reduce transportation CO_2e.

5.2. Research Limitations, Future Research Directions, and Practical Implications

The limitation of the SLDM approach is that users have to know their manufacturing activities and related factors, as well as how to quantify cost and CO_2e from them. They can learn these from the suggested factors and the pathways of each factor influencing costs and CO_2e and each TBL dimension shown in this paper. Moreover, as the approach usually gives a set of low-cost and CO_2e supply chains, users will need to know their cost and CO_2e constraints and preferences to effectively choose a final supply chain. This implies that the chosen supply chain is not necessarily the most sustainable. However, most important is that the approach shows focal firms how much the cost of a product should be when it is manufactured with environmental and social compliance, and that they should be skeptical of low product prices quoted by suppliers if the price is much lower than the calculated cost from this approach, as the suppliers may squeeze their costs via environmental and social non-compliance.

Another limitation of this paper is that the application does not include socio-economic measurement criteria. As mentioned in the model formulation section and in the pathway figure, future research can measure human health impact from CO_2e and contribution to gross domestic production at each supply stage. These measures will help link business, environmental, and socio-economic dimensions of sustainability. Furthermore, if users evaluate and compare existing supply chains, different supply chains and suppliers may have, for example, different manufacturing technologies, productivity, and difficulty in collaboration; therefore, due to the flexibility of the approach, users can adjust coefficients of manufacturing consumption among different locations and add extra relevant costs which are not suggested in this paper. Moreover, users may use our approach to find a set of low cost and CO_2e supply chains and select a final supply chain from them with qualitative criteria and approach.

Another limitation is the difficulty of data collection, though this can be lowered by choosing only one or two main suppliers per each supply stage with a limited number of potential locations. Governments can help overcome the difficulty by having a database providing all cost and emission factor data, such as electricity emission factors, import taxes, and prices of industrial water, electricity, waste collection and treatment, in order to support research and practices on sustainable supply network design, potentially resulting in industrial and sustainability improvement.

The purpose of showing the model application is to demonstrate how to use the model with real data in practice, as well as the model's potential to reveal the lowest or optimized cost and CO_2e supply chains, their most important factors, and possible local and global risks that impact the lowest cost and CO_2e supply chains. Readers should bear in mind that the results of the model application, such as the locations of the lowest cost and CO_2e supply chains and the landed cost and CO_2e, cannot be generalized because they are specific to the settings of the application in terms of product type and material, sampled locations, manufacturing consumption, and focal firm organizational contexts which influence which activities and their factors to include into supply chain cost and CO_2e calculation. Additionally, future research may test the SLDM approach in other industries, production batch sizes, and locations in order to improve the approach and possibly find patterns of common results among different industries and locations.

The SLDM approach is useful to various groups of practitioners. It allows industrial practitioners to plan and design their supply chain locations with long-term perspectives on risk factors, expansion markets, and future products with different governance levels, manufacturing batches, manufacturing technology, and recycling programs. The approach helps users understand interconnections among supply chain stages, as well as factors, activities, and outcomes leading to supply chain visibility to improve operations of different activities towards TBL sustainability in supply chains. As the sensitivity and scenario analyses during the application demonstrate that some locations cannot compete with others even if their factor values are dramatically changed, policymakers can use the SLDM approach to strategically invest resources in the factors that potentially improve their location competitiveness in terms of cost and CO_2e. The approach can help policy makers to realize which location- and distance-dependent factors should be improved to support TBL sustainability.

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Appendix A. Data Collection for the Viscose T-Shirt Application

In the below tables, the data are from data sources, application assumption, and authors' calculation based on Appendix B.

Appendix A.1. Manufacturing Data

Table A1. Cradle-to-factory gate energy use for man-made cellulose fiber manufacturing.

	Austria	China (Nanjing)	Indonesia	Great Britain	The United States	Thailand
NREU, MJ/kg [49]	19	61	61	61	61	61
REU, MJ/kg [49]	51	45	45	45	45	45
Total NREU, MJ	10,260	32,942	32,942	32,942	32,942	32,942
Total REU, MJ	27,541	24,301	24,301	24,301	24,301	24,301

Remark: NREU = non-renewable energy use, REU = renewable energy use.

Table A2. Biomass energy calorific value.

Parameter	Unit	Input Data	Remarks
Calorific values of fuel wood	MJ/kg or TJ/Gg	15.60	Excel Sheet Emission Factor Tool March 2017 [44]

Table A3. Inputs and outputs of each process in fabric and garment manufacturing.

Activity	Parameter	Unit	Calculated Data	Referred Data [48]	Remarks
Thread spinning process	Input: viscose fiber	kg	540.02	1.22	
	Electricity	kWh	2.09	0.0047222	for electricity cost and CO_2e
	Output: viscose thread	kg	442.64	1	
Knitting and dyeing process	Input: viscose thread	kg	442.64	10,886,216.88	
	Water	m^3	73.19	1,800,000	for water cost, electricity CO_2e in water waste treatment
	Electricity	kWh	6.41	157,600	for electricity cost and CO_2e
	Heat	kWh	541.34	13,313,521.07	for wood cost and CO_2e
	Output: viscose knit	kg	442.64	10,886,220	
	Solid waste	kg	97.38		for landfill CO_2e
Cutting and sewing process	Input: viscose knit	kg	442.64	1414	
	Water	m^3	0.16	0.52	for water cost and electricity CO_2e in water waste treatment
	Electricity	kWh	624.52	1995	for electricity cost, CO_2e
	Output: viscose t-shirt	kg	360.00	1150	
	Solid waste	kg	82.64		for landfill CO_2e

Table A4. Manufacturing working-time conversion.

Parameter	Unit	Input Data	Remarks
Factory working months/year	month	12	
Factory working days/month	day	26	for rent cost, solid waste cost, indirect labor cost, overheads
Number of hours per shift	hour	8	for rent cost, waste cost, indirect labor cost, overheads
Number of shifts per day	shift	2	for rent cost, solid waste cost, indirect labor cost, overheads

Table A5. Wastewater treatment electricity in fabric and garment manufacturing.

Activity	Parameter	Unit	Input Data	Remarks
Referred data from [53]	% Reclaimed water in primary water reuse system (WRS)	%	0.67	
	% Reclaimed water in secondary WRS	%	0.198	
	Used electricity rate in primary WRS	kWh/m^3	2.81	
	Used electricity rate in secondary WRS	kWh/m^3	3.8	
Knitting and dyeing process	Electricity used in primary WRS	kWh	137.88	for electricity cost and CO_2e
	Electricity used in secondary WRS	kWh	55.07	for electricity cost and CO_2e
Cutting and sewing process	Electricity used in primary WRS	kWh	0.31	for electricity cost and CO_2e
	Electricity used in secondary WRS	kWh	0.12	for electricity cost and CO_2e

Table A6. Overheads electricity consumption in fabric and garment manufacturing.

Supply Stage	Parameter	Unit	Input Data	Remarks
Referred data [58]	Monthly energy for air conditioning	kWh/month	234,000	
	Monthly energy for illuminating	kWh/month	43,200	
	For total yarn production	kg/month	401,580	
Fabric factory	Required electricity for air conditioning	kWh	257.93	for electricity cost and CO_2e
	Required electricity for illumination	kWh	47.62	for electricity cost and CO_2e
Garment factory	Required electricity for air conditioning	kWh	199.89	for electricity cost and CO_2e
	Required electricity for illumination	kWh	36.903	for electricity cost and CO_2e

Table A7. Machine and direct labor in fabric and garment manufacturing.

Activity	Parameter	Unit	Input Data	Remarks and Data Sources
Thread spinning process	Machine capacity	kg/h	51.03	[59]
	Required machine operation time	h	8.67	
	Direct labor required	person	2	
	Required labor operation time	h	17.35	for labor cost (medium-skill wage)
Yarn dyeing process	Package dyeing machine capacity	kg/h	42.50	[50]
	Required machine operation time	h	10.42	
	Direct labor required	person	2	
	Required labor operation time	h	20.83	for labor cost (medium-skill wage)
Fabric circular knitting	Machine capacity, produced fabrics	kg/h	9.54	[50]
	Number of machines	machine	2	
	Required machine operation time	h	23.20	for overhead costs
	Direct labor required	person	1	
	Required labor operation time	h	23.20	for labor cost (medium-skill wage)
	Total number of operators in factory	person	5	for certificate implementation cost
	Fabric factory productivity	%	100	
	Fabric factory working time per batch	h	23.20	for overhead cost allocation
Cutting process	Cutting machine capacity, LECTRA1	yard/minute	3.26	[51]
	Required fabric	yard	1792.89	
	Required machine operation time	h	9.16	
	Direct labor required	person	1	for labor cost (medium-skill wage)
	Required labor operation time	h	9.16	for labor cost (medium-skill wage)
Sewing process	Operation minutes for a garment	minutes	6.48	[52]
	Required machine operation time	h	194.40	
	Total number of operators	person	19	[52], for labor cost (medium-skill wage)
	Total number of helpers	person	3	[52], for labor cost (low-skill wage)
	Required labor operation time	h/person	10.23	for overhead and labor cost
	Total number of operators	person	20	for certificate implementation cost
	Total number of helpers	person	3	for certificate implementation cost
	Garment factory productivity	%	100	
	Garment factory working time per batch	h	10.23	for overhead cost allocation

Table A8. Rent and indirect labor in fabric and garment manufacturing.

Supply Stage	Parameter	Unit	Input Data	Remarks
Fabric factory including spinning and dyeing	Fabric factory size	m^2	600	for rent cost
	Plant manager	person	1	for labor cost (highest high-skill wage), certificate implementation cost
	Inspector, purchaser, sales, HR	person	4	for labor cost (use medium/average high-skill wage), certificate implementation cost
	Cleaners	person	3	for labor cost (low-skill wage), employee training cost
	Other overheads	%	10	depreciations and interest on capitals
	Profit margin	%	10	
	Total employees	person	13	
Garment factory	Garment factory size	m^2	465	for rent cost
	Plant manager	person	1	for highest-skill labor cost, employee training cost
	Inspector, purchaser, sales, HR	person	4	for average-high skill labor cost, employee training cost
	Cleaners	person	2	for low-skill labor cost, employee training cost
	Other overheads	%	10	Depreciations and interest on capitals
	Profit margin	%	10	
	Total employees	person	30	

Appendix A.2. Cost Data

Appendix A.2.1. Manufacturing-Related Cost Data

Table A9. Prices and fees of fiber, electricity, woodchip, interest, and used garments.

Manufacturing Locations	Fiber Rate, €/kg	Industrial Electricity rate, €/kWh	Woodchip Rate, €/kg	Interest Rate, %	Used garment Price, €/kg
Austria	2.29 [60]	0.10 [61]	0.06 [62]		
China (Nanjing)	1.69 [60]	0.10 [63]	0.06 [62]		1.06 [64]
Indonesia	1.77 [60]	0.07 [65]	0.07 [62]		
Great Britain	2.43 [60]	0.13 [61]	0.02 [62]		
USA	1.22 [60]	0.06 [66]	0.07 [62]		2.75 [64]
Thailand	2.11 [60]	0.07 [65]	0.05 [62]		
Germany		0.15 [61]	0.09 [62]	1.93 [67]	1.00 [64]
Italy		0.14 [61]	0.10 [62]		
Poland		0.09 [61]	0.07 [62]		
Lithuania		0.08 [61]	0.06 [62]		
Tunisia		0.05 [68]	0.13 [62]		
Egypt		0.05 [69]	0.07 [70]		
Turkey		0.06 [61]	0.07 [62]		
China (Shanghai)		0.12 [63]	0.06 [62]		
Bangladesh		0.09 [71]	0.10 [62]		
India		0.06 [72]	0.05 [73]		

Table A10. Fees and prices of industrial water, solid waste management, and rent.

Manufacturing Locations	Industrial Water Rate, €/m^3	Solid Waste Fee [1], €/year	Rent Rate, €/m^2/Month
Austria	2.82 [74]	282.45	4.62 [75]
China (Nanjing)	0.98 [76]	211.39	3.58 [77]
Indonesia	0.61 [78]	155.62	3.06 [75]
Great Britain	4.60 [74]	282.45	3.72 [79]
USA	0.90 [74]	282.45	5.05 [80]
Thailand	0.68 [81]	211.39	2.70 [82]
Germany	4.13 [83]	282.45	3.73 [84]
Italy	0.74 [74]	282.45	4.75 [85]
Poland	2.44 [74]	282.45	3.18 [86]
Lithuania	2.98 [83]	282.45	2.65 [87]
Tunisia	0.54 [88]	155.62	0.98 [89]
Egypt	0.30 [90]	155.62	2.78 [91]
Turkey	1.71 [92]	211.39	2.42 [93]
China (Shanghai)	0.98 [76]	211.39	5.96 [77]
Bangladesh	0.37 [94]	155.62	0.78 [95]
India	0.04 [96]	155.62	1.59 [97]

Remarks: [1] Based on three groups of solid waste management by country incomes, Table 5.5 in the What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050 book [98].

Table A11. Wages of helper/cleaner employees.

€/month	Minimum Wage	Living Wage for Typical Family			Low-Skilled Job Wage			Helper/ Cleaner Wage
Locations		**Lowest**	**Highest**	**Average**	**Lowest**	**Highest**	**Average**	
Austria	-	1470.00	1880.00	1675.00	1536.00	1844.00	**1690.00**	1690.00
China (Nanjing)	162.00	453.43	453.43	**453.43**	N/A	N/A	N/A	453.43
Indonesia	101.00	145.00	184.00	164.50	154.00	215.00	**184.50**	184.50
Great Britain	1517.00	1091.00	1564.00	1327.50	1344.00	1566.00	**1455.00**	1455.00
the United States	1135.00	1444.00	2094.00	**1769.00**	1221.00	1812.00	1516.50	1769.00
Thailand	**290.40**	N/A	N/A	N/A	N/A	N/A	N/A	290.40
Germany	1553.00	1520.00	2000.00	1760.00	1606.00	1997.00	**1801.50**	1801.50
Italy	-	1120.00	1510.00	**1315.00**	927.00	1205.00	1066.00	1315.00
Poland	525.00	452.00	770.00	**611.00**	517.00	608.00	562.50	611.00
Lithuania	555.00	695.00	960.00	**827.50**	401.00	489.00	445.00	827.50
Tunisia	**221.81**	N/A	N/A	N/A	N/A	N/A	N/A	221.81
Egypt	67.00	133.00	193.00	**163.00**	98.00	132.00	115.00	163.00
Turkey	320.00	405.00	584.00	**494.50**	189.00	218.00	203.50	494.50
China (Shanghai)	162.00	530.67	530.67	**530.67**	N/A	N/A	N/A	530.67
Bangladesh	16.00	144.38	174.36	**159.37**	48.00	65.00	56.50	159.37
India	52.00	195.00	286.00	**240.50**	119.00	166.00	142.50	240.50

Remarks: Numbers in bold refer to where the helper/cleaner wages in the last column (to be used as inputs for calculating labor costs) come from; Minimum wages, the lowest and highest living wages, and the lowest and highest low-skilled job wages of all countries are from WageIndicator Foundation [99] excepting of Thailand and Tunisia whose minimum wages are from Minimum-Wage.org [100].

Table A12. Operator wage.

Locations	Medium-Skilled Job Wage, €/Month			Operator Wage, €/Month
	Lowest	**Highest**	**Average**	
Austria	2125.00	2639.00	2382.00	2382.00
China (Nanjing)	205.29	481.15	343.22	453.43
Indonesia	196.00	264.00	230.00	230.00
Great Britain	1718.00	2141.00	1929.50	1929.50
the United States	1,623.00	2387.00	2005.00	2005.00
Thailand	382.79	395.87	389.33	389.33
Germany	2167.00	2826.00	2496.50	2496.50
Italy	1342.00	1678.00	1510.00	1510.00
Poland	665.00	836.00	750.50	750.50
Lithuania	513.00	655.00	584.00	827.50
Tunisia	222.04	265.93	243.98	243.98
Egypt	128.00	187.00	157.50	163.00
Turkey	206.00	263.00	234.50	494.50
China (Shanghai)	205.29	481.15	343.22	530.67
Bangladesh	50.00	76.00	63.00	159.37
India	180.00	282.00	231.00	240.50

Remarks: Number in bolds refer to living wages in Table A11 because averaged medium-skill job wages of the countries are less than the living wages; The lowest and highest medium-skilled job wages of most countries are from WageIndicator Foundation [99] excepting the Chinese wages which are from a specific study of WageIndicator Foundation [101], the Thai wages which are from Trading Economics [102], the Tunisian wages which are from Numbeo [103].

Table A13. Plant managers' and other administrative employees' wages and employer social security contribution rate.

€/Month	High-Skilled Job Wage [2]		Average Wage of Manager and Other Position	Administrative Employee Wage	Social security Contribution [104], %
Locations	**Plant Manager [1]**	**Other Position**			
Austria	6037.17	1293.75	**3665.46**	3665.46	21.38
China (Nanjing)	3062.24	518.92	**1790.58**	1790.58	32.00
Indonesia	2349.63	**1870.39**	2110.01	1870.39	9.74
Great Britain	5747.87	**5691.83**	5719.85	5691.83	13.80
USA	7265.47	**6783.39**	7024.43	6783.39	7.65
Thailand	3469.81	**1879.24**	2674.52	1879.24	5.00
Germany	7203.75	**6621.42**	6912.58	6621.42	19.83
Italy	7004.17	**6234.33**	6619.25	6234.33	30.00
Poland	3305.20	**3305.20**	3305.20	3305.20	21.00
Lithuania	8142.08	892.92	**4517.50**	4517.50	1.77
Tunisia	1859.46	142.74	**1001.10**	1001.10	16.57
Egypt	1980.44	**809.73**	1395.09	809.73	26.00
Turkey	2051.43	**2005.68**	2028.55	2005.68	22.50
China (Shanghai)	4818.76	**4195.43**	4507.09	4195.43	32.00
Bangladesh	1777.77	85.75	**931.76**	931.76	0.00
India	1814.82	1471.84	1643.33	1471.84	12.00

Remarks: [1] Plant Manager and [2] Other Position wages are from wages of 'manager' and of 'human resource and/or marketing managers' in 'career' tables appeared on the Average Salary Survey website [105], respectively. The data are based on at least 20 observations in order to be concurrent to wageindicator.org criteria. If the number of observations for each career does not reach 20 observations, the lowest and highest salaries from earning percentages, which are more than 20%, are used; Plant Manager and Administrative Employee wages are used for calculating labor costs. Administrative Employee wages are from the Other Position wages excepting when the Other Position wages of some countries are much less than their Plant Manager wages, the average of Plant Manager and Other Position wages will be used. Bold numbers indicate the sources of Administrative Employee wages.

Table A14. Cost for certificate implementation.

Maximum Turnover, €	Annual Turnover	Certificate Fee [106], £	Auditing Fee [106], £	Total Fees for Certificates and Audits for Three Years, €
117,146.00	Up to £ 100,000	995.00	450.00	1692.76
292,865.00	£ 100,000–£ 250,000	1,295.00	500.00	2102.77
585,730.00	£ 250,000–£ 500,000	1,495.00	550.00	2395.64
1,171,460.00	£ 500,000–£ 1 Million	1,795.00	600.00	2805.65
1,757,190.00	£ 1–1.5 Million	1,995.00	650.00	3098.51
2,342,920.00	£ 1.5–2 Million	2,295.00	700.00	3508.52
3,514,380.00	£ 2–3 Million	2,795.00	750.00	4152.83
5,857,300.00	£ 3–5 Million	2,995.00	850.00	4504.26

Remarks: The certificate fee is valid for three years; learning time on sustainable practices for manager and other employees are 608 and 192 h, respectively.

Table A15. Fabric testing fee with laboratory.

	£	Min, €	Max, €	Average, €	Reference
Fabric testing	45–60	52.72	70.29	61.50	[107]

Table A16. Cost and lead-time of sample delivery to laboratory and headquarters.

	Fabric XS,600 g, €/pack with Signature [108]	Garment S, 1 kg, €/pack with signature [108]	Lead-Time, Europe, Day [109]	Lead-Time, Others, Day [109]
Sample delivery cost/time	5.70	6.20	2.00	7.50
Number of sample deliveries	2	1		

Appendix A.2.2. Firm's Sustainability Assurance Cost Data

Table A17. Firm's costs and time for sustainability assurance activities.

	Flight from Dusseldorf Airport, € [110]	Domestic Travel Costs, € (Taxi or Rental Car) [111]	Fuel Costs for Rental Car, € [112]	Total Trip Time, Days	Hotel Cost [113]	Number of Car Rental Days	Number Hotel Night
Austria	299.62	153.78	20.00	3	144.00	3	2
China (Nanjing)	1762.64	42.00		6	122.00	4	3
Indonesia	1259.24	80.00		6	140.00	4	3
Great Britain	485.75	63.87	8.00	4	217.00	4	3
USA	1650.65	221.27	38.00	6	139.00	4	3
Thailand	1056.73	80.00		5	93.00	4	3
Germany	-	110.00	-	3	-	-	-
Italy	269.05	49.58	6.00	3	97.00	3	2
Poland	237.84	72.06	38.00	3	50.00	3	2
Lithuania	357.75	10.00		4	94.00	4	3
Tunisia	698.94	24.00		5	76.00	4	3
Egypt	576.45	24.00		5	44.00	4	3
Turkey	335.88	40.00		4	53.00	4	3
China (Shanghai)	904.78	50.00		6	167.00	4	3
Bangladesh	1292.11	12.00		6	102.00	4	3
India	984.09	12.00		6	74.00	4	3

Appendix A.2.3. Logistics-Related Cost Data

We searched logistics costs from the websites Searates.com [114] and Worldfreightrates.com [115] and freight insurance from the website Freightinsurancecenter.com [116]. Ship and truck insurance rates are 0.87 and 0.55 euro for every 100 euro of free on-board value of insured goods, with a minimum fee of 45 euros. Import duties were retrieved from the website simplyduty.com [117]. Number 1–16 in Tables A18–A22 refer to manufacturing locations in Austria, China (Nanjing), Indonesia, Great Britain, the United States, Thailand, Germany, Italy, Poland, Lithuania, Tunisia, Egypt, Turkey, China (Shanghai), Bangladesh, and India, respectively.

Table A18. Costs of transportation by truck and ship among the 16 manufacturing locations.

From/to	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	to
1	0	451	451	451	585	451	**0.06**	**0.05**	**0.07**	**0.11**	451	451	451	451	451	451	0.03
2	567	0	451	458	647	451	464	451	451	451	451	624	583	**0.01**	480	451	0.01
3	451	451	0	451	738	451	451	451	451	451	451	451	451	451	451	451	0.00
4	451	552	451	0	504	451	451	451	451	451	451	451	451	552	716	582	0.00
5	665	734	917	459	0	934	451	594	503	523	594	733	683	734	1246	1006	0.02
6	451	451	451	451	752	0	451	451	451	451	451	451	451	451	451	451	0.01
7	**0.06**	542	451	451	495	451	0	**0.07**	**0.08**	**0.12**	451	451	451	542	702	571	0.02
8	**0.05**	451	451	451	558	451	**0.07**	0	**0.11**	**0.16**	451	451	451	451	501	571	0.02
9	**0.07**	597	451	451	547	451	**0.08**	**0.11**	0	**0.05**	451	451	451	597	612	506	0.03
10	**0.11**	620	451	451	568	451	**0.12**	**0.16**	**0.05**	0	451	463	451	620	636	526	0.02
11	451	451	451	451	558	451	451	451	451	451	0	451	451	451	501	451	0.03
12	451	451	451	451	711	451	451	451	451	451	451	0	451	451	482	451	0.02
13	451	451	451	451	663	451	451	451	451	451	451	451	0	451	451	451	0.00
14	567	**0.01**	451	458	647	451	464	451	451	451	451	624	583	0	480	451	0.00
15	451	451	451	548	726	451	538	451	466	484	451	451	451	451	0	451	0.02
16	451	451	451	518	687	451	509	451	451	457	451	451	451	451	451	0	0.02
from	0.03	0.01	0.00	0.00	0.02	0.01	0.02	0.01	0.03	0.02	0.03	0.02	0.00	0.00	0.01	0.02	

Remarks: Bold refers to truck cost in euro per kilogram and the rest is ship transportation price per ton in euro for the less-than-container load; the last column and row refer to truck cost in euro per kg to/from a port from/to a factory, respectively.

Table A19. Import duty percentage for used garments (HS code 63090000).

From/To	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	5.3	0	0	5.3	0	30	5.3	5.3	5.3	5.3	20	35	0	0	0	25
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	5.3	14	35	5.3	0	30	5.3	5.3	5.3	5.3	20	35	5.3	14	0	25
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	14	35	0	0	30	0	0	0	0	20	0	0	14	0	25
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	5.3	0	0	5.3	0	30	5.3	5.3	5.3	5.3	20	35	0	0	0	25
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A20. Import duty percentage for viscose t-shirts (HS code 6114300000).

From/To	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0	18	0	0	28	0	0	0	0	0	0	0	0	18	0	0
2	12	0	0	12	28	0	12	12	12	12	0	0	12	0	0	0
3	9.6	0	0	9.6	28	0	9.6	9.6	9.6	9.6	0	0	9.6	0	0	0
4	0	18	0	0	28	0	0	0	0	0	0	0	0	18	0	0
5	12	18	0	12	0	0	12	12	12	12	0	0	12	18	0	0
6	12	0	0	12	28	0	12	12	12	12	0	0	12	0	0	0
7	0	18	0	0	28	0	0	0	0	0	0	0	0	18	0	0
8	0	18	0	0	28	0	0	0	0	0	0	0	0	18	0	0
9	0	18	0	0	28	0	0	0	0	0	0	0	0	18	0	0
10	0	18	0	0	28	0	0	0	0	0	0	0	0	18	0	0
11	0	18	0	0	28	0	0	0	0	0	0	0	0	18	0	0
12	0	18	0	0	28	0	0	0	0	0	0	0	0	18	0	0
13	0	18	0	0	28	0	0	0	0	0	0	0	0	18	0	0
14	12	0	0	12	28	0	12	12	12	12	0	0	12	0	0	0
15	0	18	0	0	28	0	0	0	0	0	0	0	0	18	0	0
16	9.6	18	0	9.6	28	0	9.6	9.6	9.6	9.6	0	0	9.6	18	0	0

Table A21. Import duty percentage for viscose fabrics (HS code 6006320000).

From/To	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0	10	10	0	10	0	0	0	0	0	20	0	0	10	0	25
2	8	0	0	8	10	0	8	8	8	8	20	10	0	0	0	25
3	0	0	0	0	10	0	0	0	0	0	20	10	0	0	0	25
4	0	0	0	0	10	0	0	0	0	0	20	0	0	10	0	25
5	8	10	10	8	0	0	8	8	8	8	20	10	8	10	0	25
6	8	0	0	8	10	0	8	8	8	8	20	10	0	0	0	25
7	0	10	10	0	10	0	0	0	0	0	20	0	0	10	0	25
8	0	10	10	0	10	0	0	0	0	0	20	0	0	10	0	25
9	0	10	10	0	10	0	0	0	0	0	20	0	0	10	0	25
10	0	10	10	0	10	0	0	0	0	0	20	0	0	10	0	25
11	0	10	10	0	10	0	0	0	0	0	0	0	0	10	0	25
12	0	10	10	0	10	0	0	0	0	0	20	0	0	10	0	25
13	0	10	10	0	10	0	0	0	0	0	20	0	0	10	0	25
14	8	0	0	8	10	0	8	8	8	8	20	10	0	0	0	25
15	0	0	0	0	10	0	0	0	0	0	20	10	0	0	0	25
16	0	8.5	8.3	8	10	0	0	0	0	0	20	10	0	8.5	0	0

Table A22. Import duty percentage for viscose fiber staplers (HS code 5504100000).

From/to	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0	5	5	0	4.3	0	0	0	0	0	0	0	0	5	0	20
2	4	0	0	4	4.3	0	4	4	4	4	0	0	4	0	0	20
3	0	0	0	0	4.3	0	0	0	0	0	0	0	0	0	0	20
4	0	0	5	0	4.3	0	0	0	0	0	0	0	0	5	0	20
5	4	5	5	4	0	0	4	4	4	4	0	0	4	5	0	20
6	4	0	0	4	4.3	0	4	4	4	4	0	0	4	0	0	20

Appendix B. Cost and Carbon Dioxide Equivalent (CO2e) Computations for the Viscose T-Shirt Application

Appendix B.1. Manufacturing Cost and CO2e Computations

Manufacturing costs in each supply stage ($cost_M$) are calculated by summing the results of Equations (A1)–(A14), the other overhead costs, and profits. Recycling costs can be calculated with the same equations. All input and output amounts and time shown in the equations are for one-batch manufacturing. Unspecified acronyms refer to factors in Figure 2 shown in the paper. The materials cost of the initial stage (d) can be calculated by Equation (A1a). If the cost $rate_{Mi}$ for inputs of the initial stage (d) is the Ex Works (EXW) price at the factory at the earlier stage (d-1), logistics costs from d-1 to d location has to be included. Material $cost_{Mi}$ of subsequent stages (c and b) is calculated from the summation of manufacturing costs of the previous stage (d or c) with logistics costs (from d to c or c to b), as shown in Equation (A1b).

$$\text{Material cost}_{\text{Mi, d}} = \text{Amount}_{\text{Mi}} \times \text{Cost rate}_{\text{Mi}} \tag{A1a}$$

$$\text{Material cost}_{\text{Mi for c or b}} = \text{Cost}_{\text{M at d or c}} + \text{Cost}_{\text{L, d to c or c to b}} \tag{A1b}$$

Direct and indirect employee costs are calculated according to Equations (A2)–(A4).

$$\text{Direct labor cost}_{\text{Mhd}} = \text{Mt} \times \text{Number of people}_{\text{Mhd}} \times \text{Hourly wage}_{\text{ Mhd}} \tag{A2}$$

$$\text{Indirect labor cost}_{\text{Mhi}} = (\text{Mt or T}_{\text{B}}) \times \text{Number of people}_{\text{Mhi}} \times \text{Hourly wage}_{\text{ Mhi}} \tag{A3}$$

$$\text{Administrative employee cost}_{\text{Mha}} = \text{T}_{\text{B}} \times \text{Number of people}_{\text{Mha}} \times \text{Hourly wage}_{\text{Mha}} \tag{A4}$$

where T_B refers to total factory-working time of each batch. Hourly wage refers to industrial wages or occupational wages for workers and positions of different skill levels. The wages have to be equal to or higher than the living wage of each location. If not, living wages should be used in order to ensure human rights, social equality, and socio-economic sustainability.

Costs of water, electricity, and onsite heating can be calculated by Equations (A5)–(A7)

$$\text{Water cost}_{\text{Mw}} = \text{Amount}_{\text{Mw}} \times \text{Cost rate}_{\text{Mw}} \tag{A5}$$

$$\text{Electricity cost} = \text{Amount}_{(\text{Mep+Mew+Meo})} \times \text{Electricity cost rate} \tag{A6}$$

$$\text{Heat cost}_{\text{Mb}} = \text{Amount}_{\text{Me}} \times \text{Wood price} \times \text{Wood calorific values of fuel wood} \tag{A7}$$

Wastes can be treated onsite or by a service provider. If waste treatment occurs at the factory, involving electricity for the treatment has to be calculated as shown in Equation (A6). Depending on how factories pay fee to the service provider, cost of solid waste treatment can be calculated by Equations (A8a) or (A8b) based on amount and time, respectively. In Equation (A8a), solid waste amount from processing can be from the difference between inputs and outputs. Equation (A8b) is used when the fee is a flat rate per year.

$$\text{Solid waste cost}_{Ms} = \text{Amount}_{Mws} \times \text{Cost rate}_{Mws} \tag{A8a}$$

$$\text{Solid waste cost}_{Ms} = T_B \times \text{Yearly fee}_{Ms}/T_F \tag{A8b}$$

where T_F refers to factory working hours per year.

Costs of factory rent, as well as sample check and delivery are calculated by Equations (A9) to (A11).

$$\text{Rent}_{Mr} = T_B \times \text{Monthly fee}_{Mr}/T_F/12 \tag{A9}$$

$$\text{Sample check fee}_{Msf} = \text{Lab test fee}_{Msf}/N_B \tag{A10}$$

$$\text{Sample delivery cost}_{Msd} = \text{Postal cost}_{Msd} \times \text{Number of delivery}_{Msd}/N_B \tag{A11}$$

where N_B is the number of production batch which is used for allocating sample check costs into the number of batches produced with the tested materials or components and the checked product sample.

Costs relating to sustainability assurance activities performed by manufacturers are calculated by Equations (A12)–(A14) for acquiring and implement sustainability certificates and for employer social security contribution.

$$\text{Certificate fee}_{Mcf} = (\text{Certificate fee}_{sMcf} + \text{Auditing fee}_{Mcf}) \times T_B/(\text{Number of certified year} \times T_F) \tag{A12}$$

$$\text{Employee training cost} = \text{Learning time}_{Mcm,Mco} \times \text{Hourly wage} \times T_B/(\text{Total certified year} \times T_F) \tag{A13}$$

$$\text{Social security cost}_{Mc} = \text{Rate}_{Mc} \times (\text{Cost}_{Mhd} + \text{Cost}_{Mhi} + \text{Cost}_{Mha} + \text{Employee training cost}) \tag{A14}$$

For the other overhead costs, users may use actual costs from factories or estimate them by multiplying a percentage with the summation of Equations (A1)–(A14). After that, profit margins of manufacturers at d, c, and b stages can be estimated by multiplying a percentage with the summation of Equations (A1)–(A14) and the other overheads cost. The percentages for the other overheads and profit margin depend on industries. Finally, the summation of Equations (A1)–(A14), the other overheads cost, and the profit margin is EXW price of materials, components, or products to the next supply chain tier/stage. The summation of EXW price and logistics costs to the location of the next stage is landed cost of materials, components, or products.

Manufacturing CO_2e is derived from the summation of CO_2e from activities relating to factors shown in Figure 2 at each d, c, and b manufacturing locations. Each activity CO_2e is calculated by Equation (A15).

$$CO_2e = ((EF_{CO2} \times GWP_{CO2}) + (EF_{CH4} \times GWP_{CH4}) + (EF_{N2O} \times GWP_{N2O})) \times \text{Manufacturing rates} \tag{A15}$$

where Manufacturing rates, which are defined in Step 3 of the proposed approach, are amounts of consumed electricity for processing (Mep), waste treatment (Mew), and light/air/overheads (Meo), of heat generated onsite by biomass (Me), of solid wastes to landfill (Mws), and of delivered samples (Msd) and distance from factories to the headquarter and laboratory for quality and chemicals checking. Each EF collected in Step 5 is aligned to each factor of manufacturing activity rates. These CO_2e computations can be applied for computing CO_2e from the recycling process.

Appendix B.2. Logistics Cost and CO2e Computations

Logistics cost is calculated by summing international transportation, freight insurance, domestic transportation to/from ports in case of ship, import duties, and port fees shown in Equation (A16).

$$\text{Cost}_L = \text{Cost}\,(_{Lm,\ Lw\ or\ Ls,\ Ld}) + \text{Cost}_{Li} + \text{Cost}_{Lt} + \text{Cost}_{Lo} + \text{Cost}_{Ll} \tag{A16}$$

The transportation and insurance costs can be obtained from logistics providers or from the multiplication of size and/or weight of transported goods and distance data from Step 3 with transportation cost rates from Step 4. The import duties can be calculated by multiplying import duty rates from Step 4 with the summation of EXW price of transported goods, domestic and international transportation costs, and insurance cost.

Logistics CO_2e can be calculated by multiplying distance data from Step 3 with EFs of transportation mode from Step 5 and use GWP for CO_2e conversion. Logistic CO_2e for each transportation route from d to c, c to b, and b to a are calculated by Equation (A17).

$$CO_2e_L = ((EF_{CO2} \times GWP_{CO2}) + (EF_{CH4} \times GWP_{CH4}) + (EF_{N2O} \times GWP_{N2O})) \times \text{Weight} \times \text{Distance} \tag{A17}$$

CO_2e_L includes both domestic and international transportations and their EFs depend on transportation mode. Cost and CO_2e from reverse logistics to recycling locations are also calculated by Equations (A16) and (A17).

Appendix B.3. Firm's Sustainability Assurance Activity Cost and CO2e Computations

Firm's sustainability-assurance costs relate transportation, hotel, and manager costs to visit a factory and interests on capital for firm's cash flow ensuring business sustainability. They are calculated according to Equations (A18)–(A22). Costs relating to a factory visit are allocated into the number of production batches before the next visit of an employee from headquarter for new styles and products as well as for solving problems.

$$Cost_F = Cost_{Fh} + Cost_{Ft} + Cost_{Fm} + Cost_{Fi} \tag{A18}$$

$$Cost_{Fh} = \text{Hotel night rate} \times \text{Number of travelling nights for a factory visit}/N_B \tag{A19}$$

$$Cost_{Ft} = (\text{Domestic transportation costs} + \text{International transportation cost})/N_B \tag{A20}$$

$$Cost_{Fm} = \text{Hourly wage} \times \text{Number of travelling hours}/N_B \tag{A21}$$

$$Cost_{Fi} = \text{Yearly rate}_{Fi}/365 \times (\text{Total cost}_M + \text{Total cost}_L + Cost_{Fh} + Cost_{Ft} + Cost_{Fm}) \times LT \tag{A22}$$

where LT is total lead time from manufacturing, logistics, and firm activities.

Sustainability Assurance CO_2e relates only the employee transportation including both domestic and international transportations of passengers. Their EFs depend on transportation mode. Passenger transportation CO_2e is calculated according to Equation (A23).

$$CO2e_F = ((EF_{CO2} \times GWP_{CO2}) + (EF_{CH4} \times GWP_{CH4}) + (EF_{N2O} \times GWP_{N2O})) \times \text{distance} \tag{A23}$$

Appendix C. Analysis Results from the Viscose T-Shirt Application

Appendix C.1. Cost and Carbon Dioxide Equivalent (CO2e) Ranking Results

Table A23. The 16 lowest cost and CO_2e supply chains for the European market and their cost and CO2e values for 1800 t-shirt manufacturing.

Rank	Low-Cost Supply Chain	€	Low-CO_2e Supply Chain	kgCO_2e
1	US-EG-EG	7768	AT-AT-AT	6122
2	ID-EG-EG	7777	AT-DE-DE	6190
3	US-TN-TN	7921	AT-DE-AT	6198
4	CN(N)-EG-EG	7973	AT-AT-DE	6248
5	TH-EG-EG	8051	AT-DE-GB	6393
6	CN(N)-TN-TN	8074	AT-IT-AT	6392
7	ID-TN-TN	8134	AT-AT-IT	6406
8	AT-EG-EG	8215	AT-DE-IT	6431
9	GB-EG-EG	8301	AT-AT-LT	6438
10	TH-TN-TN	8408	AT-IT-DE	6460
11	ID-TR-TR	8520	AT-DE-LT	6462
12	US-TR-TR	8521	AT-AT-GB	6483
13	AT-TN-TN	8572	AT-GB-DE	6503
14	US-PL-PL	8634	AT-LT-AT	6511
15	GB-TN-TN	8658	AT-GB-AT	6543
16	AT-PL-PL	8685	AT-IT-IT	6548

Remarks: Alternative names refer to locations of fiber, fabric, and garment manufacturing; and AT = Austria, CN (N) = China (Nanjing), ID = Indonesia, GB = Great Britain, US = the United States, TH = Thailand, DE = Germany, PL = Poland, IT = Italy, LT = Lithuania, TN = Tunisia, EG = Egypt, TR = Turkey.

Appendix C.2. Important Cost and CO2e Factors by Stacked Column Charts

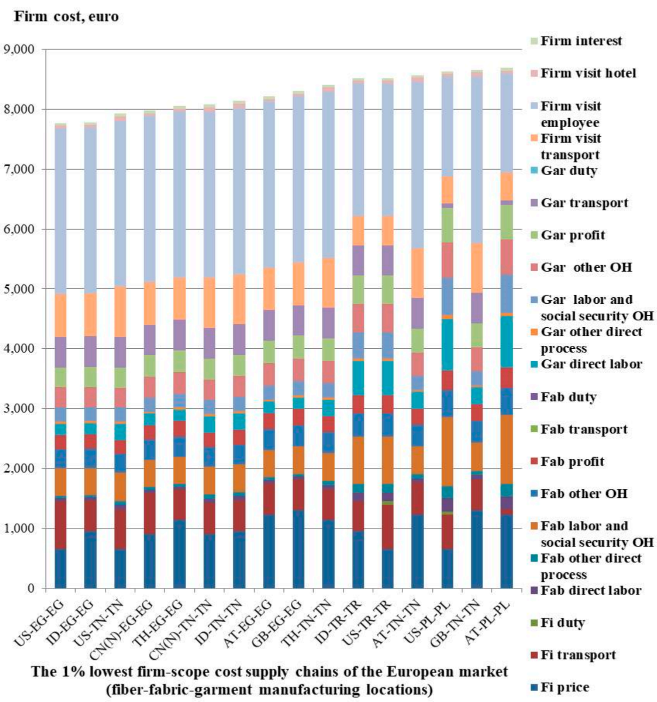

Figure A1. Breakdown costs of the 16 lowest cost supply chains for one 1800 t-shirt batch. Remarks: Fi, Fab, and Gar refer to fibers, fabrics, and garments; OH is overheads; and AT = Austria, CN(N) = China (Nanjing), ID = Indonesia, GB = Great Britain, US = the United States, TH = Thailand, DE = Germany, PL = Poland, TN = Tunisia, EG = Egypt, TR = Turkey.

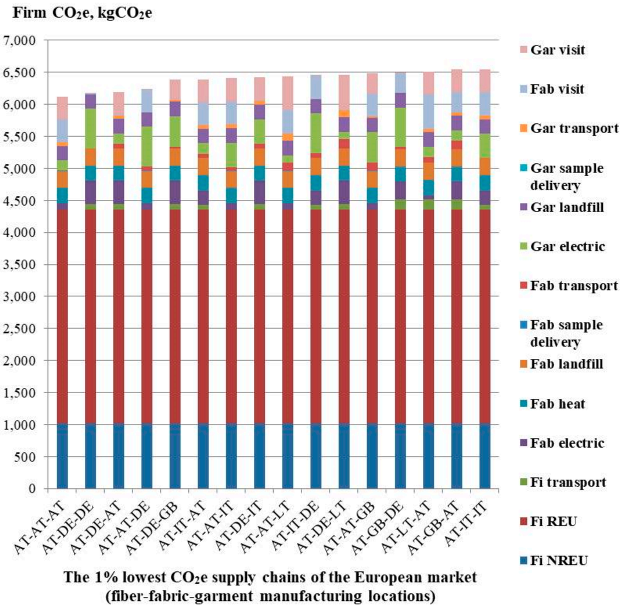

Figure A2. Breakdown CO_2e of the 16 lowest CO_2e supply chains for one 1800 t-shirt batch. Remarks: Fi, Fab, and Gar refer to fibers, fabrics, and garments; NREU and REU are non-renewable and renewable energy use; and AT = Austria, GB = Great Britain, DE = Germany, IT = Italy, LT = Lithuania.

Appendix C.3. Optimized Cost and CO2e Pareto Supply Chains by a Scatter Plot

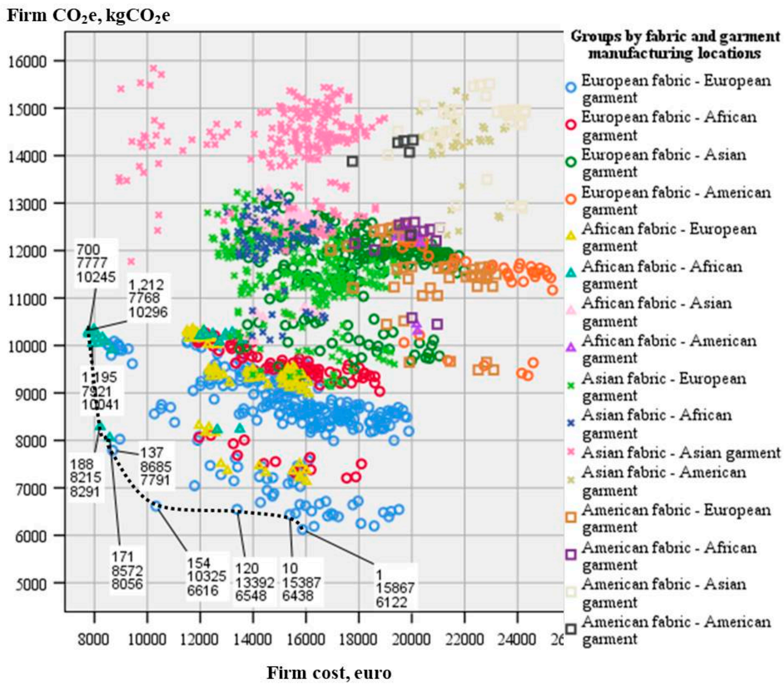

Figure A3. Optimized low cost and CO_2e supply chains on the Pareto frontier of the categorical scatter plotting between the firm-scope costs and CO_2e of all 1536 possible supply chains for a 1800-t-shirt batch. Remarks: Each supply chain on the Pareto frontier shows index number to fiber, fabric, and garment manufacturing locations, as well as its cost and CO_2e; 1 = AT-AT-AT, 10 = AT-AT-LT, 120 = AT-IT-IT, 154 = AT-LT-LT, 137 = AT-PL-PL, 171 = AT-TN-TN, 188 = AT-EG-EG, 1195 = US-TN-TN, 700 = ID-EG-EG, 1212 = US-EG-EG; and AT = Austria, ID = Indonesia, US = the United States, IT = Italy, PL = Poland, LT = Lithuania, TN = Tunisia, EG = Egypt.

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