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Research Article

Balancing Cost and Environmental Impact: A Linear Programming Approach to Sustainable Shopping

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Abstract:

A linear programming model is devised for consumer purchasing decisions minimizing weighted cost and environmental impact using real-world data. Minor shifts towards environmental preferences can greatly reduce impact with minimal cost increase. Spending slightly more on the bundle than the cheapest option can cut environmental impact by a third. Conversely, less than 10% compromise in impact yields over 15% cost savings. Consumers can find efficient midpoints—cost-effective and environmentally sustainable options—through strategic decisions. Additionally, a synthetic dataset, modeling different societal dispositions through Beta distributions of cost-environment orientation parameters, simulates societal attitudes, showing that a 10% reduction in environmental impact is possible with a 23% higher economic burden, while 60% of this reduction can be achieved with only 3.1% increase in cost when maintaining a balanced societal disposition. This demonstrates the potential of optimization-based strategic purchasing decisions to achieve significant economic and environmental efficiencies when accompanied by increased environmental awareness.

1. Introduction

As the impacts of global warming become increasingly evident across various regions, environmental awareness driven by protocols, agreements, and regulations is being propagated from the state level downwards. Firms adopt sustainable practices in their process and product designs. Although we have various tools to understand and measure the dimensions of sustainability at this level, there is no analytical decision-making model specifically tailored to shopping preferences at the retail level.

The primary interface between individuals and sustainable decision-making is the purchase of products and/or services that undergo various stages. These life cycle phases extend into the realm of individual households, physical stores, and e-commerce platforms. Throughout these stages, products and services generate environmental, economic, and social impacts on systems. With growing interest in greener products and access to product information, sustainability has become crucial for retail companies aiming to attract customers.

Investigation of the effect of carbon dioxide (CO_2) and greenhouse gases (GHG, see Table 1 for a list of acronyms, abbreviations and notation used) on the climate goes back to the 19th Century [1]. Over more than a century, numerous scientific research studies by institutes and companies have examined the effects of industrial systems and greenhouse gases on the Earth, with action plans beginning in the 21st century. Today, there is no scientific doubt that human-sourced industrial activities are warming the planet and creating risks to human life. Climate change refers to long-term changes, often associated with global temperatures, extreme weather events, and more, due to high concentrations of greenhouse gases such as CO_2, methane (CH_4), nitrous oxide (N_2O), and fluorinated gases.

GHG emissions are categorized into five sectors by the the Intergovernmental Panel on Climate Change (IPCC): Energy Systems; Industry; Agriculture, Forestry, and Other Land Use (AFOLU); Transport;

and Buildings. In 2018, the highest emissions were from the energy systems sector (34%), followed by industry (24%), AFOLU (21%), transport (14%), and buildings operations (6%) [2].

IPCC classification system is structured around five broad sectors. However, when evaluating environmental impacts at the product level, such as a t-shirt or a car, the classification does not capture the extensive variety of product categories and their specific life cycle phases. This broad categorization aggregates emission values across entire sectors, making it difficult to accurately assess the environmental impacts of individual products.

To ensure that greenhouse gas concentrations do not have a dangerous impact on the climate; the Kyoto Protocol was signed in 1997 and the Paris Agreement entered into force in 2016. With these binding agreements, impact on the environment has been taken more seriously by governments. This also leads industries to measure their current impact and transform their businesses with more sustainable product, process and practices.

Sustainability is defined as “meeting the needs of the present without compromising the ability of future generations to meet their own needs” [3]. There is a strong connection between sustainability and climate change. Sustainable practices aim to reduce greenhouse gas emissions and mitigate the impacts of climate change to ensure a healthier planet for future generations. However, sustainability is a broader concept that encompasses the mitigation of impacts in various categories, such as reducing water footprint, ozone depletion, resource depletion, and land/forest use. While climate change is a crucial aspect of sustainability, it's essential to recognize that addressing it should not come at the expense of neglecting other environmental impacts.

Table 1. *Acronyms, abbreviations and notation used.*

Acronym/Abbreviation/Notation	**Definition**
c_{ik}	The price of model k in category i
e_{ik}	The environmental impact of model k in category i
EPD	Environmental product declaration
GHG	Greenhouse gas
GRI	The Global Reporting Initiative
GWP	Global warming potential
HA	Hybrid algorithm
I	Product category index set (e.g., milk, bread, eggs)
i	i is an element of I
IPCC	The Intergovernmental Panel on Climate Change
η	Parameter aligning cost and impact components of objective function
J	The set of indices for products
j	Index indicating a product
K_i	Brand/Model set for each product category *i*
Kg CO2-eq	Kilograms of CO_2 Equivalent
LCA	Life cycle assessment
LP	Linear Programming
M_i	The minimum required quantity for product category *i*
MILP	Mixed Integer Linear Programming
MOLP	Multiobjective Linear Programming
NLP	Nonlinear Programming
v_{ik}	Volume or quantity of one sale unit of product *k* category *i*
w_1	Weight assigned to cost in the objective function
w_2	Weight assigned to environmental impact in the objective function
W_k	Weight or importance of sustainability criterion k
x_{ij}	Quantity of product j to be purchased from supplier i
y_i	Binary variable, 1 if supplier i is selected, 0 otherwise
Z	Decision variable indicating the objective value of the MOLP problem

Sustainability is defined by three essential dimensions: environmental, economic, and social. Each dimension significantly impacts the assessment of a product, process, or system's sustainability, as every industrialized product affects these areas. Goods, vehicles, buildings, and services generate carbon emissions throughout their life cycles, encompassing material extraction, production, transportation, usage, and end-of-life disposal. These stages not only add economic value but also engage societal elements like the labor force, while contributing to impacts in numerous critical categories such as water depletion, ozone and metal depletion. This lifecycle perspective is crucial in understanding and addressing the broad impact of consumer goods on global sustainability. Sustainability applications span various sectors, including business practices, urban development, and individual lifestyle choices, with technological innovations in renewable energy, sustainable agriculture, and waste management playing key roles.

Measuring sustainability involves assessing environmental, economic, and social factors that influence many corporate and public decisions. Effective measurement frameworks provide insights into current performance and guide future improvements and compliance with international standards. Companies begin this process by aligning with regulations to assess the environmental impacts of their processes and products. Life cycle assessment (LCA) has become an essential tool in this regard [4], enabling the evaluation of potential environmental impacts and resource use throughout a product’s lifecycle. An Environmental Product Declaration (EPD) complements this by offering a transparent, third-party verified report that assesses a product's environmental impact, aligned with the ISO 14025 standard [5]. This process includes phases from raw material extraction to end-of-life management, with EPD results measured in various environmental impact units such as the global warming potential (GWP in grams of CO_2-equivalent), acidification potential (in grams of SO_2-equivalent) and water scarcity potential (in m^3 of water-equivalent) [6].

Research across disciplines such as marketing, sociology, anthropology, and cultural geography has extensively explored shopping behaviors [7], revealing that 77% of European citizens prefer environmentally friendly products as consumers and are willing to pay a premium for them if the environmental benefit is indicated [8]. However, skepticism about the environmental claims made by brands highlights the need for transparent environmental product systems [9]. This skepticism drives the demand for clear, credible information that can significantly influence consumer decisions and support the integration of sustainability into everyday shopping behaviors, as discussed by Stöckigt et al. (2018) [10] and O’Rourke and Ringer (2016) [11]. This perspective underscores the importance of transparency in environmental reporting, particularly in the retail sector where the suitability of purchasing environmentally friendly products is crucial.

In the retail sector, particularly focusing on supermarket goods, sustainability is not just a corporate responsibility but also a crucial aspect of consumer behavior. The retail industry, which is projected to grow significantly by 2029 [12], plays a substantial role in the global economy and employment [13]. The economic dimension of sustainability in retail focuses on activities that support long-term economic health and development, considering their social and environmental impacts. The economic performance indicators used to assess sustainability include metrics such as net sales, cost of goods, and geographic breakdown of markets [14]. These indicators help integrate sustainability into business strategies to optimize both environmental and economic outcomes.

Furthermore, sustainability measurement in retail incorporates social aspects through corporate social responsibility (CSR) initiatives. Companies use social certifications to demonstrate their commitment to ethical practices, with social indicators devised by Global Reporting Initiative (GRI) providing a framework for assessing the social impacts of business operations [14].

Sustainability-focused optimization models in retail use various methodologies, such as Linear Programming (LP), Mixed-Integer Linear Programming (MILP), and others, to evaluate and enhance sustainability practices across all three dimensions [15]. In a review article [16], 25 articles that applied OR tools to address sustainable engineering challenges have been noted, prevalent topics being logistics and scheduling. The review underscores the importance of Multi-Criteria Decision Making (MCDM) in resolving diverse engineering problems, ranging from traffic management to location selection and healthcare.

Mishra (2020) [17] observes that despite the inherent challenges posed by conflicting criteria and non-comparable functions in multi-criteria problems, identifying optimal solutions remains achievable. This suggests a growing sophistication in addressing sustainability through advanced optimization techniques.

However, despite these advancements, there remains a significant gap in fully addressing the consumer decision-making process regarding environmentally friendly product choices. This gap underscores the need for further research and development in integrating environmental considerations into consumer shopping behaviors, thereby fostering a more sustainable retail environment. The optimization model developed in this study addresses the need for tools that help consumers make sustainable purchasing decisions by accounting for products' life cycle impacts alongside their impacts on consumer budget.

2. Modeling Sustainable Retail: A Multi-objective Linear Programming Problem

The primary objective of this research is to develop a mathematical model that optimizes consumer purchasing decisions in retail shopping, considering both cost and environmental impact. The model aims to fill the gap in existing literature where optimization methods have been extensively applied to sustainable supply chain management but not to individual consumer decisions.

There is an increasing public interest in sustainability, driven by greater awareness and more stringent regulations. Consumers are more inclined to buy environmentally friendly products, and regulatory frameworks are pushing for more sustainable practices. This research seeks to bridge the gap by utilizing Multi-objective Linear Programming (MOLP) to minimize both the cost and environmental impact of products in a consumer's shopping list.

The model integrates real-world data, including products that have an associated EPD and their respective prices, to provide a practical tool for optimizing retail purchasing decisions. Ultimately, the goal in this study is to demonstrate the potential of optimization methods as effective tools for sustainable consumer decision-making.

To facilitate the analysis, datasets representing shopping lists and supermarket inventories are required. The model initially utilizes realistic data from a small selection of products but is subsequently tested with an expanded synthetic dataset encompassing hundreds of product entries to ensure robustness and scalability, as discussed in Section 3.

The primary dataset is compiled using supermarket products that hold EPD certificates [5]. Prices are gathered from various online supermarket platforms, with only those products featuring both price information and EPD certificates included in the analysis. While GWP is a significant metric for assessing climate change impacts, it is essential to acknowledge that GWP is not the sole representative of overall environmental impacts. Carbon footprint, often measured in equivalent grams/kilograms of CO_2 emissions (kg CO_2-eq), is a widely used indicator due to its direct link to climate change and its global implications. However, a comprehensive environmental assessment requires consideration of other critical categories, such as water footprint, metal depletion, terrestrial acidification, and biodiversity loss. These factors are interconnected and can have significant consequences for ecosystems, human health, and economies.

While carbon footprint is not the only indicator of environmental impact, it serves as a valuable proxy due to its widespread influence across the supply chain. Energy and fuel consumption throughout various stages, from raw material extraction to farming, transportation, and production, contribute significantly to carbon emissions. Therefore, despite being just one category among many critical environmental impacts, carbon footprint provides a comprehensive representation of a product's environmental performance from beginning to end. Additionally, carbon emissions contribute significantly to global warming, a pressing environmental issue with far-reaching consequences. Addressing climate change is a matter of urgency, making carbon footprint a relevant and timely metric. Moreover, climate change is a widely recognized issue, making carbon footprint a familiar concept to consumers that can be effective on their decisions.

In this study, we focus on carbon footprint as a representative of environmental impacts to create a multicriteria framework that balances economic and environmental considerations in retail shopping. This approach allows for a practical and actionable framework that can be implemented in various retail settings.

The mathematical model aims to optimize purchasing decisions of individuals in retail shopping, focusing on two main criteria under an MOLP approach: cost and environmental impact. This approach is suitable for balancing multiple, often conflicting, objectives.

With the notation including index definitions, parameters and decision variables introduced in Table 2, the MOLP is formulated by the objective function (1), the purchase quantity fulfillment constraints (2) and the variable sign and integrality constraint (3) as follows:

Table 2. *Notation used in the formulation of the MOLP.*

Index Set	Description
I	Index set for each category such as milk, bread, eggs; $i \in I$.
K_i	Index set for all product brand/models under product category $i \in I$. Each product is uniquely defined by its specific attributes such as brand and size.
Parameter	**Description**
c_{ik}	The price of product *k* in category *i* per one unit of sale.
e_{ik}	The environmental impact of product *k* in category *i* per one unit of sale.
v_{ik}	Amount in volume or mass of one sales unit of product *k* in category *i* per one unit of sale.
M_i	The minimum required quantity for the product category i
w_1/w_2	The weight given to cost/environmental impact components according to how the customer prioritizes each. $w_2 = 1 - w_1$.
η	Parameter for aligning cost and environmental components on a comparable scale.
Decision Variable	**Description**
x_{ik}	The quantity of product *k* purchased from category *i*, in number of sale units. The variable is integer valued.

$$Z = w_1 \sum_{i \in I} \sum_{k \in K_i} c_{ik}\, x_{ik} + \eta\, w_2 \sum_{i \in I} \sum_{k \in K_i} e_{ik}\, x_{ik} \quad (1)$$

$$\sum_{k \in K_i} v_{ik}\, x_{ik} \geq M_i, \forall i \in I \quad (2)$$

$$x_{ik} \geq 0,\ x \in \mathbb{Z},\ \forall i \in I, \forall k \in K_i \quad (3)$$

The decision variables x_{ik} represent the quantity of model *k* selected from product category *i*. These decision variables are integers, reflecting the actual number of products to be purchased. The objective function is the weighted sum of total cost and total environmental impact, where C_{ik} denotes the cost of selecting model k from product category *i*, and e_{ik} denotes its environmental impact. Here, the weights w_1 and w_2 are parameters representing the decision-maker's prioritization between cost and environmental considerations $w_1 + w_2 = 1$. With these weights, the orientation of the objective with respect to price and environmental footprint is adjusted. $\eta = Z_1/Z_2$ is the factor brining the two components of the objective to similar scales in regard to their minimum attainable values in the solution space, i.e., $Z_1 = \min \sum_{i \in I} \sum_{k \in K_i} c_{ik}\, x_{ik}\ subject\ to\ (2)-(3)$, and $Z_2 = \min \sum_{i \in I} \sum_{k \in K_i} e_{ik}\, x_{ik}\ subject\ to\ (2)-(3)$. The constraints of the model ensure that shopping list requirements in terms of category amounts are met. (2) guarantees the purchase of sufficient quantity from each product category, where v_{ik} represents the amount of demand in category *i* satisfied by one unit of product k, and M_i represents the minimum required amount for category *i*. (3) enforces that the decision variables x_{ik} are non-negative and integer, ensuring that the solutions are practical and applicable in a real-world retail setting. The mathematical model (1)-(3) has been coded in Python 3.10, and solved using PuLP 2.8.0.

The Pareto diagram in Fig. 1 is a graphical representation of the trade-offs between two competing objectives: total cost (€) and total environmental impact (kg CO_2-eq). The curve represents the Pareto-efficient frontier, which consists of solutions where no objective can be improved without worsening the other. This indicates that all points on this frontier are Pareto-optimal solutions given the trade-offs between cost and environmental impact. The inverse relationship between the two objectives and how changes in weight affect the optimization results is visible in Fig. 1. Additionally, the Pareto-efficient frontier is convex shaped, thus, there are efficient midpoints where the consumer can balance economic and environmental concerns, achieving the larger fractions of the economic savings and environmental preservation possible.

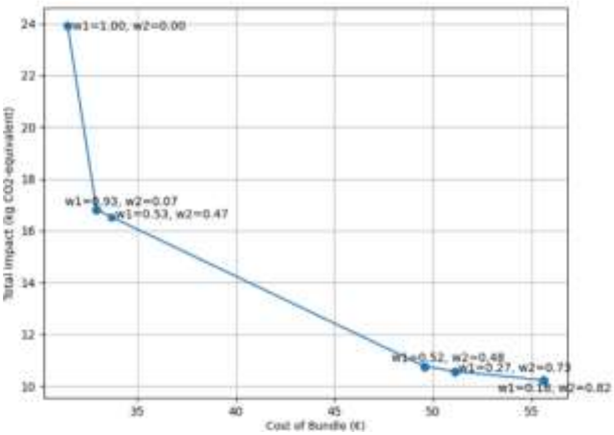

Figure 1. *MOLP Pareto-efficient frontier for the range of relative weights for cost and environmental perspectives.*

The Pareto diagram and the detailed shopping choices at different weight values illustrate the trade-offs between cost and environmental impact in consumer purchasing decisions. The breakpoints indicate critical regions where significant shifts in the rate at which cost versus impact trade-off, offering guidance to consumers on aligning their purchases with sustainability goals and budget constraints. At the break points, slight variations in the weights assigned to cost and environmental criteria, such as a change from w_1=0.52 to w_1=0.53, can lead to substantial differences in outcomes. Although the change in weight is minor, it can result in notable shifts in both cost and environmental impact, underscoring the sensitivity of the results to even minimal adjustments in input parameters. This phenomenon is particularly pronounced due to the discrete nature of the decisions in this study.

Adding to this discussion, the extreme orientations with respect to cost and environment demonstrate a wide range in terms of environmental outcomes. An entirely cost-oriented approach can incur costs as low as 32 € for the bundle, at an environmental burden of 24 kgs CO_2 -eq. Conversely, a focus purely on environmental concerns without budget constraints can lead to costs exceeding 55 €, while significantly reducing the environmental impact to around 10 kgs CO_2 -eq. This range is illustrated by the convex structure of the trade-off curve, highlighting that consumers do not have to adhere to extremes to find value.

Indeed, by opting for a balance between cost and environmental considerations, consumers can locate efficient midpoints that offer substantial benefits. For instance, by investing just a few euros above the lowest cost bundle, a consumer can reduce the environmental impact by a third, achieving more than half the maximum environmental benefit observed in the highest cost, environmentally focused bundle. Conversely, with less than a 10% increase in the GWP impact of the bundle—a small fraction of the overall range in environmental burden—savings of more than 15% are achievable compared to the most environmentally friendly option. Thus, consumers can make purchasing decisions strategically, with moderate adjustments attaining significant gains in both economic and environmental aspects.

3. Modeling Societal Orientations and Environmental Outcomes

In this section, we introduce a synthetic and fictive dataset designed to explore the interplay between consumer purchasing behavior, cost, and environmental impact in the retail context. The dataset encompasses 277 products spanning 59 product categories. Each product is characterized by specific attributes, including the quantity in its respective unit, a price tag, and an environmental impact label that considers the burden from supply, production, to market shelf.

The synthetic dataset is entirely fictive and is not derived from real product or sustainability databases. The aim is to provide a robust analysis of the potential impacts of different consumer orientations on overall cost and environmental outcomes in a retail setting.

Each product category is purchased by retail shoppers with a certain probability. The probabilities representing the likelihood of retail shoppers purchasing each product category are assigned based on subjective estimates. If a purchase occurs, the amount the shopper desires to buy follows a lognormal distribution with a known mean and standard deviation (Table 3). This approach allows for the modeling of realistic purchase quantities and reflects the variability observed in actual consumer behavior.

Table 3. *Sample rows from the fictive dataset of product categories. Probability of purchase from each category in a shopping list, mean and standard deviations of purchased amount if there is a purchase.*

Product Category	Purchase Probability (%)	Mean	Standard Deviation	Unit
Baby Foods	30	130	40	g
Baked Goods	48	340	75	g
Baking Supplies	34	395	225	g
Juice	11	1000	500	ml

To capture the diversity in societal orientations towards environmental concerns and sustainability consciousness, we consider seven distinct groups with different societal orientations. These orientations are represented by a distribution of customer types, indicating an individual's inclination towards being cost-oriented or environmentally oriented. This inclination is quantified by the parameters w_1 and w_2 in the optimization model described by equations (1)-(3) in Section 2.

The societal orientations are represented by Beta probability distributions, which have a bounded range in the interval (0, 1) and can be flexibly shaped by two parameters α and β of the distribution. The parameters are both shape parameters jointly determining the unique probability density function. They have symmetric effect on the variance, $\mathrm{Var}(X) = \frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)}$, however α constitutes the nominator of the mean $E[X] = \frac{\alpha}{\alpha+\beta}$, where $X \sim Beta(\alpha, \beta)$. Thus, the magnitude of α relative to

β increases the mean shifting the distribution left, while increasing both parameters simultaneously reduces the variance. This is visible in Fig. 2, as for instance, Group 2 with larger α/β ratio compared to Group 1 is relatively shifted to right, and Group 4 with relatively small α and β values has a spread out distribution with a large variance. The Beta family encompasses a wide range of distribution shapes, from highly right-skewed distributions that are asymptotic to x=0 (indicating a heavy accumulation at low values) to milder right-skewed distributions, symmetric distributions with varying levels of deviation from the mean 1/2, and left-skewed distributions with high accumulation at larger values.

Seven groups, each representing a distinct societal disposition towards economic and environmental concerns, are devised for modeling collective purchasing behavior. Beta distributions modeling these groups characterize the balance between economic and environmental priorities. The specific shape parameters, α and β, for these distributions are detailed in Table 4. Diverse societal orientations are represented, ranging from those extremely environmentally oriented with minimal regard for cost (low w_1 values) to those at the opposite extreme, which prioritize cost over environmental concerns (high w_1 values). These extreme orientations are not necessarily the norm. The symmetric distribution Beta (2.5, 2.5) represents a balanced societal orientation towards both economic and environmental concerns (Fig. 2). The two distributions on each side of the symmetry reflect varying degrees of shift towards sustainability or economic ends. With increasing environmental awareness and sustainability education, a societal shift towards an environmentally oriented society can be expected, as represented by Group 1 with the most right-skewed distribution Beta (10.0, 90.0).

Table 4. *Distribution parameters for groups representing different societal orientations towards economic and environmental aspects.*

Distribution	α	β
Group 1	10.0	90.0
Group 2	6.0	24.0
Group 3	4.5	10.5
Group 4	2.5	2.5
Group 5	10.5	4.5
Group 6	24.0	6.0
Group 7	90.0	10.0

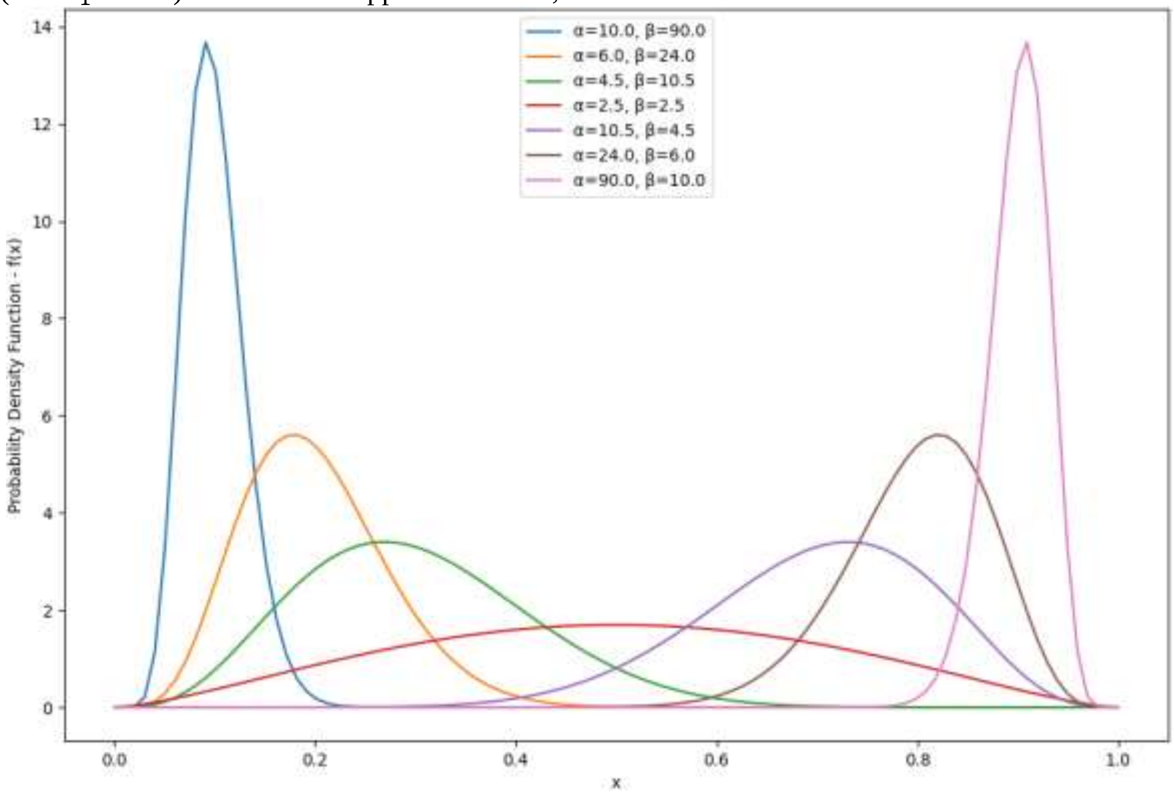

Figure 2. *The probability density functions of distributions from the Beta family defining the societal orientations of Groups 1,…,7 towards economic ($w_1 = x$) versus environmental ($w_2 = 1 - x$) concerns.*

Each customer sampled from a group $i \in \{1, \dots, 7\}$ has a type parameter randomly chosen from the group specific distribution ($w_1 \sim Beta(\alpha_i, \beta_i)$, $i = 1, \dots, 7$). The sampled customer decides whether to purchase from each product category independently, according to the probabilities as exampled in Table

3. For categories from which the sampled customer decides to purchase, the purchase amount is sampled from the respective distribution for the product category. The mean and standard deviations for the purchase amount distributions are exampled in Table 3. Weighing cost and environmental impact components in (1) according to her/his type w_1, the customer chooses an optimal bundle according to the model (1)-(3) discussed in Section 2.

Table 5 displays the mean and standard deviations of the cost and environmental impacts of bundles purchased by 10000 customer samples from each of the distributions. Additionally, the table displays the mean and standard deviations of the cost and environmental impact outcomes when all samples are pooled together, considering three cases: the individuals purchase entirely cost oriented bundles (assuming $w_1 = 1$ for all), they purchase entirely environmentally concerned bundles (assuming $w_1 = 0$ for all), or they purchase according to their own types (w_1 as sampled from respective distributions).

Table 5. *Comparative analysis of cost and environmental impact for different societal dispositions.*

Population	Cost (€)		Impact (kg CO_2-eq)	
	Mean	**Stdev**	**Mean**	**Stdev**
Overall*, Cost Minimizer	35	12.4	10.2	4.4
Overall, Impact Minimizer	44	15.1	9.2	4
Overall, Weighted	36.6	12.9	9.6	4.1
Group 1, Weighted	39.3	13.5	9.2	3.9
Group 2, Weighted	37.9	13.3	9.3	4
Group 3, Weighted	37.1	12.9	9.4	4
Group 4, Weighted	36.1	12.6	9.6	4.1
Group 5, Weighted	35.4	12.4	9.9	4.2
Group 6, Weighted	35.1	12.4	9.9	4.2
Group 7, Weighted	35	12.5	10	4.2

*Overall: Customer shopping lists pooling samples from all 7 groups. Cost minimizer: (1)-(3) is solved for each customer assuming $w_1 = 1$ (sample size n = 70000). Impact minimizer: (1)-(3) is solved for each customer assuming $w_1 = 0$ (sample size n = 70000). Weighted: (1)-(3) is solved with w_1 as sampled from the indicated distribution of the group; Group 1, …,7 (sample size n = 10000 for each); or the pool of samples from Group 1,…,7 (“overall” - sample size n = 70000). Stdev: standard deviation.

The sample means for cost ranges in 35.0-44.0, as set by the cost minimizing and entirely environmentally concerned ends. Impact changes inversely, with a range 9.2-10.2.

With this specific fictive dataset, the cost range for economic versus environment optimized ends corresponds approximately to 23% of the maximum, and impact range corresponds to 10% of its own scale. On the shelf, on average, a consumer can find products that have a 13% smaller carbon footprint and are 12% less expensive than the products with the lowest cost and lowest environmental impact per-unit, respectively. Thus, these figures in the two ends are significant: 10% impact reduction achievement is limited by what the product range on the shelf has to offer in terms of environmental savings. Purchases are in integer amounts, and sales frequencies for product categories are not uniform, thus 23% economic savings is possible overall. There is clearly an opportunity to save significantly with small difference in environmental impacts, when the customer perspective slightly shifts to incorporate economic concern besides environmental concern (Fig. 3, comparing overall cost minimizer to Group 1). From the opposite end, the economically next best in each category saves a moderate 2% (one fifth of the achievable range) in impacts with slight increase in the cost of the bundle (Fig. 3, comparing overall impact minimizer to Group 7). For different societal dispositions, mean bundle cost and impact indicates a convex pattern (Fig. 3), thus balancing economic and environmental concerns, it is possible to achieve significant proportions of maximum attainable savings in both aspects.

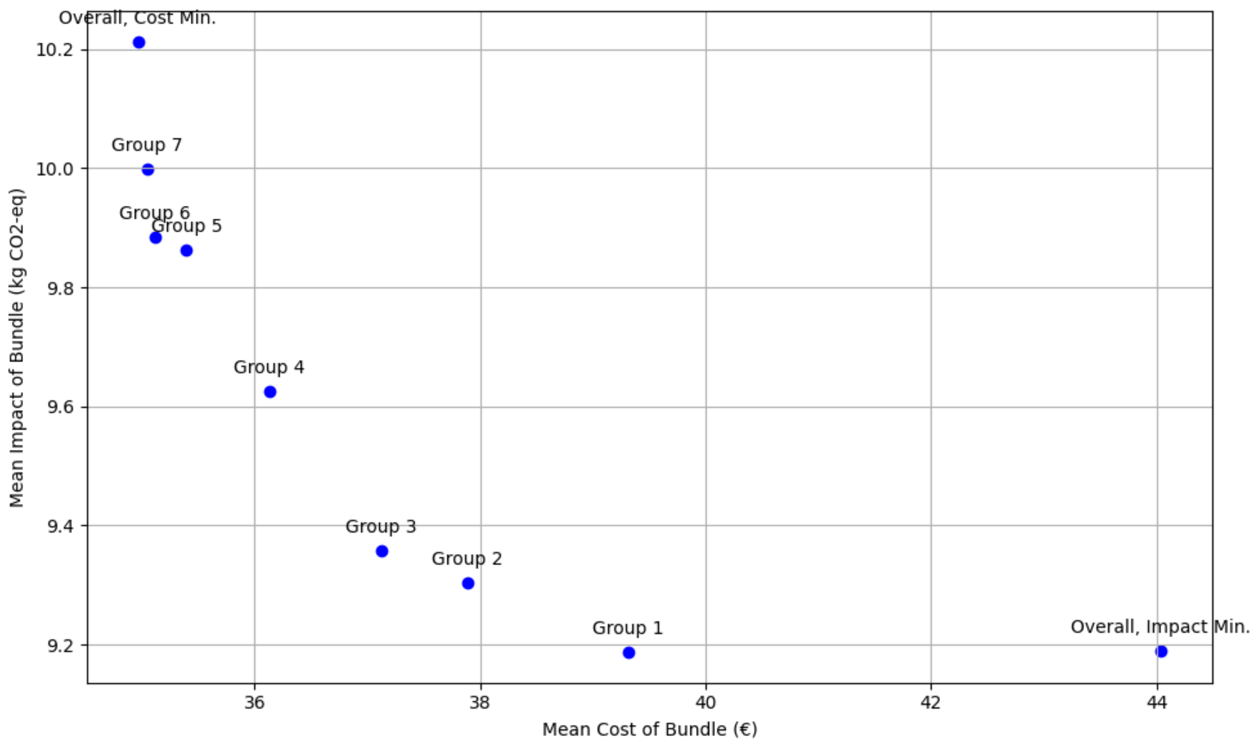

Figure 3. *Mean cost and environmental impacts of bundles purchased according to entirely economic or environmentally oriented customers, and customers sampled from Group 1, …, Group 7.*

The shift in the distribution of the cost and environmental impact of bundles for sampled customers aligns with that of the sample means. The most drastic shift occurs between the totally environmentally oriented sample and Group 1, where half of the attainable savings are achieved with the slight cost prioritization introduced alongside the environmental perspective (Fig. 4, left). Further prioritization of the cost does have such marginal yield in savings. Impact histograms indicate smaller shifts in distribution with changes in orientation (Fig 4., right). However, in compliance with the convex pattern (Fig. 3), they oppose the cost histograms in direction. Where cost distributions visibly shift leftwards, as seen in the shift from a totally environmental orientation to Group 1, impact distributions slightly shift to the right. Relatively larger shifts in the increasing direction occur for impact distribution as the cost orientation in society becomes more pronounced (Fig. 4, right).

Overall, a 10% reduction in environmental impact is achieved when society shifts to a fully environmentally concerned orientation, which incurs a 23% higher economic burden—9 € per bundle on average. However, 60% of this reduction is accomplished with only a 1.1 € (3.1%) increase in the cost of an average bundle when society maintains a balanced disposition regarding cost and environmental impact (Group 4). The environmental preservation range is 80% achieved with a 2.1 € (6%) increase in mean bundle expense (Group 3). A society prioritizing the environment over cost almost fully attains the impact reduction by paying 4.3 € (12%) more on the grocery shopping bundle on average. This demonstrates the importance of education and awareness campaigns, highlighting how societal environmental awareness can significantly reduce impacts with relatively small increases in expense when such awareness exists.

This analysis demonstrates the utility of the devised multi-objective customer choice model in capturing the nuanced interplay between economic and environmental considerations in consumer decision-making. The synthetic dataset allows for a robust examination of how different societal orientations, represented by various Beta distributions, impact overall cost and environmental outcomes in retail purchasing. Even slight shifts towards environmental consciousness can yield substantial reductions in environmental impact with minimal additional costs. Thus, public education and awareness campaigns can play a crucial role in promoting more sustainable consumer behavior.

4. Conclusions

This study suggests the multiobjective optimization of consumer purchasing decisions in retail shopping, with a dual focus on cost and environmental impact.

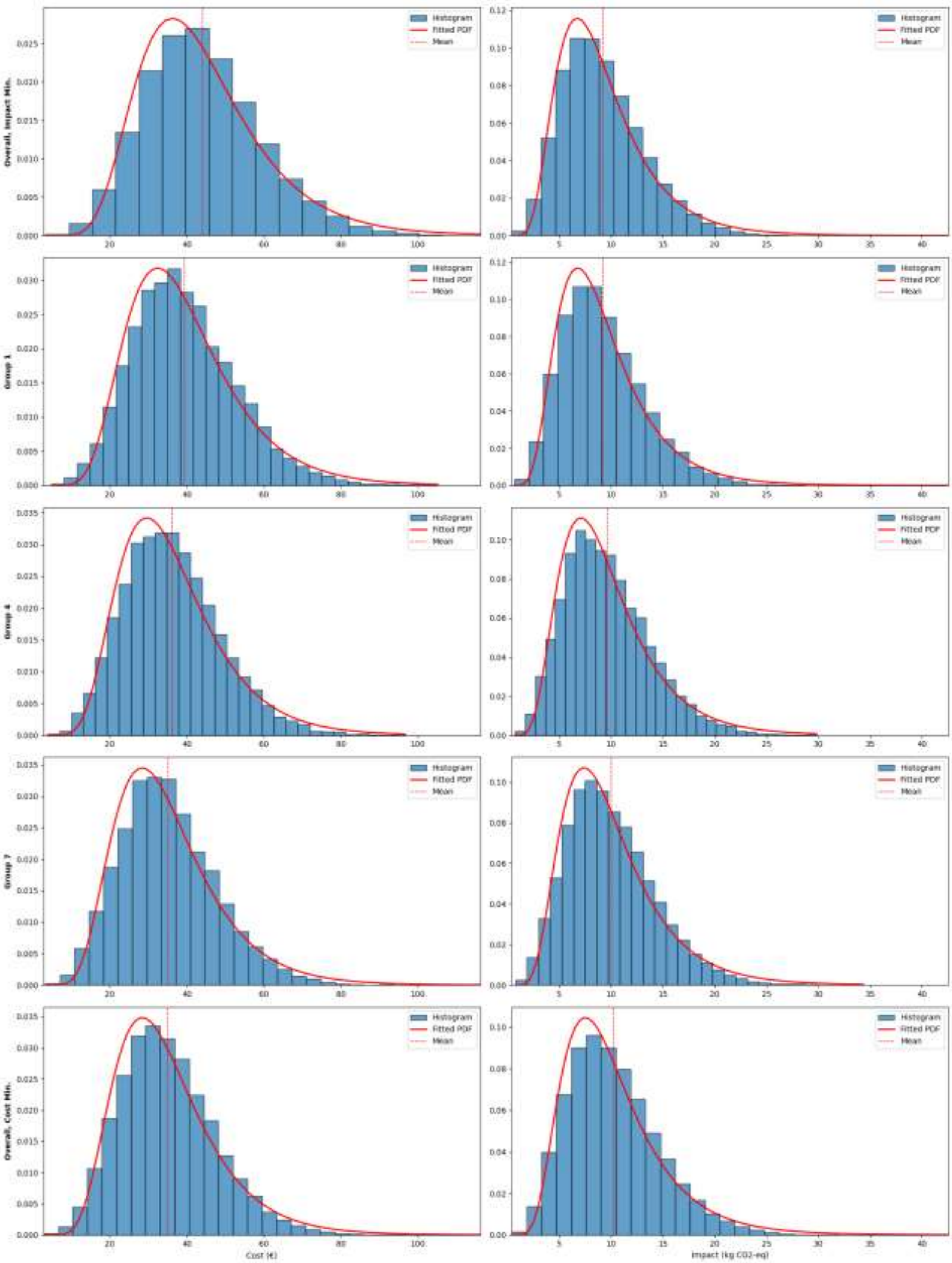

Figure 4: *Histograms for cost (left) and impact (right) distributions for optimal bundles of overall impact minimizer, Group 1, Group 4, Group 7, and overall cost minimizer samples. Lognormal density is fitted on top for comparabilty.*

This model fills a significant void in existing literature by extending optimization techniques beyond sustainable supply chain management to encompass individual consumer choices. Utilizing real-world data sources, including EPDs and product pricing, the model offers a tangible tool for consumers aiming to make informed, sustainable purchasing choices.

The analysis reveals that minor shifts in the weights assigned to cost and environmental considerations can significantly alter outcomes, emphasizing the model's sensitivity and utility in exploring a spectrum of customer attitudes. As exampled by a fictive case, a small expense above the minimum cost can reduce environmental impacts substantially, achieving over half the maximum environmental benefit attainable at the highest cost, environmentally focused purchasing scenario. Conversely, one kg CO_2-eq (less than 10%) increase in environmental impact results in nearly 15% (from 56 € to 49 €) cost savings compared to the most eco-friendly choices.

A recurring challenge during this study was the limited access to comprehensive environmental impact data for commonly available supermarket products. The model's applicability could be significantly enhanced with access to more extensive EPDs and LCA results. This would enable a more refined analysis and improve the model's utility. Moreover, the model can be readily extended to incorporate a multitude of additional impact criteria, including water footprint, metal depletion, ozone depletion, terrestrial acidification, and human toxicity, provided sufficient data and comprehensive impact modeling is available.

By simulating different societal orientations using Beta distributions, an analysis with a fictive dataset demonstrates that even slight shifts towards environmental consciousness can yield substantial reductions in environmental impact with minimal additional costs. This finding emphasizes the critical role of public education and awareness campaigns in fostering more sustainable consumer behaviors.

From this analysis, two key recommendations emerge for suppliers. First, there is a clear need for a more detailed and comprehensive assessment of environmental impacts and footprints, including carbon, water, and metal depletion footprints, across their products. Second, in relation to product development, it is evident that as environmental awareness grows, the importance of designing and selecting environmentally friendly processes will become as significant as cost considerations in product design.

This analysis focuses on the consumer side of the decision-making process, assuming a fixed supply chain landscape in terms of products, prices, and environmental impacts. A bilevel extension could incorporate a supplier decision-making layer, where the supplier determines product processes and materials, influencing prices and impacts. The consumers then choose their bundles based on preferences. Such a model would assist producers in designing environmentally conscious products aligned with market preferences and illuminate the impact of consumer attitudes on product design.

Limitations in this study include the assumption of deterministic consumer acceptance, where consumers are always expected to follow optimization-based suggestions. In reality, consumer behavior is more complex, can be influenced by factors like brand loyalty, and there can be resistance to product suggestions due to established purchasing habits. Probabilistic models could better capture the likelihood of consumers choosing products that deviate from their preferred brands or cost more.

Additionally, the study focuses primarily on carbon footprints, neglecting other important environmental impact categories such as water footprint, metal depletion, terrestrial acidification, and biodiversity loss.

To address the limitations, future research could explore stochastic models for consumer behavior, incorporate additional environmental impact categories into the multicriteria framework, and employ alternative multicriteria modeling approaches such as ε-constraints for different impact categories with different targets and priorities. Furthermore, developing comprehensive action plans based on the identified environmental impacts and investigating the interconnections between impact categories could contribute to effective sustainability strategies. By addressing these limitations and exploring these future directions, future research can provide a more comprehensive and effective understanding of environmental sustainability in retail shopping.

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