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Article

Decision-Making Platform for Design Optimization by Integrating Linear Programming and House of Quality

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Abstract. This study presents an integrated approach combining the House of Quality (HoQ) and Linear Programming (LP) to optimize the design and manufacturing of consumer beverage packaging, ensuring alignment between customer expectations and engineering capabilities. The methodology focuses on translating user needs into functional characteristics, while minimizing production costs and material waste to support sustainability efforts. Linear Programming (LP) is utilized to systematically evaluate various design alternatives, helping designers strike an optimal balance between performance, usability, and cost-efficiency. Additionally, Finite Element Analysis (FEA) is applied to simulate mechanical behaviors, addressing structural concerns like handling convenience and base stability. Special attention is given to design elements, the ergonomically contoured body and cap, with an emphasis on single-handed operation and force distribution. The final design incorporates a sleek, minimalist aesthetic, enhancing both user interaction and manufacturing feasibility. This integrated framework not only enhances development efficiency but also aligns with changing market trends, especially among younger consumers who value functional aesthetics and responsible design. By bridging customer insights with engineering analysis, this study offers a strategic pathway for creating innovative and sustainable packaging solutions.

Keywords: Beverage packaging, product design and development, quality function deployment, house of quality, decision-making and optimization, linear programming.

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1. Introduction

The research team has meticulously undertaken the task of transforming customer desires into tangible and actionable design recommendations—an approach encapsulated by the "desire-to-design" concept. This strategy seeks to maximize customer satisfaction and enhance sales performance during new product launches. It involves a dual approach: refining existing products to enhance durability and user experience, while simultaneously developing entirely new designs within the same product category to address the diverse needs of segmented consumer groups. The application of Product Design and Development (PDD) is essential. PDD supports a structured pathway through which design teams can systematically apply a concept from early sketches to fully developed, manufacturable products. This structured process not only reduces material waste and shortens the development cycle but also minimizes the cost of trial-and-error iterations. The emphasis is on maintaining production efficiency and high-quality outcomes, which are especially critical in competitive markets where customer expectations are constantly changing.

Within the PDD framework, the Concept Development (CD) and Detailed Design phases play pivotal roles. During these stages, tools such as Quality Function Deployment (QFD) and the House of Quality (HoQ) are extensively utilized to translate the voice of the customer into engineering specifications. These tools serve as bridges between consumer expectations and technical feasibility, enabling the design team to ensure that product features, performance metrics, and functional attributes are closely aligned with market demand. Once the HoQ is developed, it reveals the correlation between customer needs and the functional attributes required to meet them. These correlations are then translated into specific physical design parameters that define the product's form and function [1–3]. While cost, logistics, and storage considerations are occasionally integrated into the HoQ matrix, they are often addressed only superficially. This limited integration can result in product designs that, although functionally robust, are financially inefficient due to high development or manufacturing costs.

To address this disconnect, the incorporation of Linear Programming (LP) is proposed as a complementary optimization tool. LP is a well-established mathematical technique employed across engineering, management, and economics for resource allocation and decision-making under constraints [4–6]. It is particularly effective in solving real-world problems involving competing objectives and limited resources. In the realm of engineering design, LP has been applied to optimize project budgeting, streamline logistics, and manage resource allocation in sectors such as construction, transportation, and agriculture [7–10]. When integrated with the HoQ framework, LP offers the ability to expand a single "master design" into multiple alternative configurations. These alternatives retain the core functional characteristics but vary in their cost, component complexity, or production feasibility. This capability enables the design team to evaluate a range of options and select the optimal design based on quantitative trade-offs between performance and investment. By leveraging LP, the design process becomes not only more responsive to customer needs but also more economically and operationally efficient.

Key contributions and broader impact are presented on *highlighting innovation and novelty*, this study introduces a hybrid approach that links QFD-driven design frameworks with LP optimization. By embedding customer-function linkages into the design process and then applying LP to explore and prioritize design alternatives, the method allows for greater innovation. It facilitates the generation of multiple viable design configurations that balance performance, feasibility, and cost, leading to more informed and strategic decision-making.

For *quantifying practical benefits*, the combined use of HoQ and LP results in a measurable reduction in production costs, material waste, and development time. By eliminating redundant components and refining design specifications early in the process, this approach supports sustainability goals and contributes to streamlined manufacturing workflows. The LP model enables quantitative assessment of design options, ensuring that resources are used effectively and efficiently throughout the development lifecycle.

For *addressing industry needs*, this research directly engages with the needs of engineers and designers working in the field of sustainable product development. It responds to challenges in balancing consumer-driven innovation with practical constraints such as budget, production efficiency, and market readiness. In particular, this methodology is well-suited for applications like beverage packaging, where design must be both aesthetically appealing and functionally optimized for production, storage, and transportation. By aligning technical development with market expectations, the framework supports the creation of competitive products that resonate with the target customer base.

2. Related Works

To demonstrate the practical application of the proposed decision-making framework, this study employs the design of a small-scale volume drinking container as a case study, integrating Linear Programming (LP) and House of Quality (HoQ) methodologies to generate innovative and optimized bottle designs. This approach is particularly valuable for startup ventures and small to medium-sized enterprises engaged in conventional beverage production and packaging. The study addresses both internal characteristics—such as beverage sensory attributes—and external characteristics, including form, ergonomics, and aesthetic appeal of the bottle design. The outcomes establish a foundational basis for future implementation and serve as a set of actionable guidelines for applying this integrated decision-making platform in product design and development.

2.1. Sensory Analysis

In the food and beverage sector, sensory analysis is an important method for understanding what customers like and for supporting marketing decisions [11]. Although it has been widely used in food development, it is also very useful for beverages [12]. By studying elements like taste, smell, texture, and appearance, developers can check if the product matches what customers expect. A key part of this process is finding out which sensory features affect how much customers like a beverage. This can be done using descriptive sensory analysis, where trained people carefully describe and rate the product's sensory qualities [13]. This method gives detailed information that helps connect specific features of a drink to customer opinions.

Newer sensory analysis techniques, such as "check-all-that-apply" (CATA) and "rate-all-that-apply" (RATA), let regular consumers (not just trained testers) give feedback. These methods help collect more complete information about how people experience and prefer certain drinks. This allows developers to better understand customer needs and improve products. When creating drinks, the mix of different sensory features is very important. The way sweetness and sourness work together, especially in drinks made with sugar and citric acid, can either increase or reduce the effect of each. Carbonation also affects how people feel the taste. These relationships must be considered to make sure the final product tastes right and is well-liked [14].

To find the best taste based on what customers enjoy, developers can use quantitative descriptive analysis (QDA). This helps clearly describe the product's features and shows which ones are most important for customer approval. By combining sensory analysis with taste tests from different customer groups, companies can discover which combinations are most preferred [15]. These results help guide drink recipes and show where new products could succeed. Sensory analysis not only improves current drinks but also supports the creation of new ones.

In addition to taste and feel, the design of the bottle—called the product's external features—is also very important for how customers choose products. While internal features are about taste and other sensory qualities, external features include how the packaging looks and how easy it is to use. The House of Quality (HoQ) method has shown how customer wishes can be turned into product designs, including both the sensory parts and the physical container. HoQ helps connect customer needs with technical details to make sure the final product matches what people want. Even though things like cost, shipping, and storage are sometimes only partly included in the HoQ process, they still help guide design decisions to make products more competitive in the market.

2.2. Bottle and Package Design

For a small-scale volume drinking container, creating an ergonomic shape that fits comfortably in the hand helps improve grip and ease of use. Lightweight, eco-friendly materials like recycled PET [16, 17] or biodegradable plastics [18, 19] reduce environmental impact. Using bright colors or unique patterns [20, 21] can attract consumer attention and reflect the beverage's flavor or theme, while also providing ample space for branding and important product information. A user-friendly screw cap or flip-top design makes opening easier while preserving freshness [22, 23]. Transparent sections or textured surfaces add visual interest and allow consumers to see the drink inside, while a slightly wider base ensures stability for stacking and storage.

Eco-friendly features, such as lightweight construction or reusable components, support sustainable practices [24, 25]. Options like double-wall designs can help control beverage temperature, while added functions like built-in straws or pour spouts offer convenience, especially for on-the-go consumers [26, 27].

Modern package design must also reflect shifting consumer preferences, particularly among teenagers and young adults. This group values personal expression, trend-based designs, and social interaction [28, 29]. Adding customizable features—such as removable labels, covers, or special edition graphics—can create a closer emotional link between the user and the product [30 - 33].

Design elements that integrate with digital tools, such as QR codes leading to online content or interactive brand experiences, extend the user experience and enhance brand engagement [34, 35]. Eco-friendly materials and refillable options resonate strongly with this generation, as they are more environmentally conscious and often prefer brands that demonstrate responsibility [36, 37]. By blending creative, functional, and sustainable design elements, brands can develop beverage packaging that not only captures attention but also meets the practical needs and lifestyle values of today's consumers.

2.3. Customers' Perceptions and Attention Toward Beverage Purchasing Decisions

Customers' perceptions and attention toward beverage purchasing decisions are influenced by several factors, including brand reputation, as established brands often attract consumers due to trust and recognition [38, 39]. Eye-catching and innovative packaging designs can draw attention and significantly impact purchase choices [40, 41]. Taste and quality remain top priorities, with consumers relying on reviews and recommendations [42, 43]. Health consciousness plays an important role, as many customers consider nutritional information and opt for beverages that align with their health goals [44, 45]. Sustainability is increasingly important, with eco-friendly packaging and production practices resonating with environmentally conscious consumers [46, 47]. Competitive pricing also affects purchasing decisions, especially in budget-sensitive markets [48, 49]. Additionally, effective marketing strategies, including a strong social media presence and promotional campaigns, can influence consumer choices, while recommendations from friends, family, or influencers can strongly influence beverage selections [50, 51]. Understanding these factors enables brands to tailor their strategies to better meet customer expectations and drive purchasing decisions.

2.4. Product Design and Development

Product design and development (PDD) is the process of creating new and effective products that a company or business group can sell to customers. Design encompasses the creation of a product's style and feel, as well as its manufacturing process and materials, while development refers to creating a product that appeals to customers and testing and modifying it until it is ready for production [52]. Typically, PDD consists of five main stages, integrating House of Quality (HoQ) and Quality Function Deployment (QFD) methodologies to ensure customer needs are met throughout the process during concept development stage:

For *concept development*, this stage focuses on identifying customer needs, establishing the target group, and performing competitive analysis. The output is design guidelines that include material choices, design alternatives, product attributes in terms of customer requirements, distinctive points of the product, and business goals.

For *system level design*, this stage involves defining the system, interfaces, features, and functions of a product, addressing part components, engineering parameters, and determining alternative approaches for achieving the product's specifications in the next stage.

For *detailed design*, the task of this stage is to define part geometry or specification, texture, cost of production, and manufacturing process. Tooling and materials used are also prepared.

For *testing and refinement*, prototypes are built and tested to evaluate their performance. If the product is not acceptable, it should be redesigned in the previous stage.

For *production ramp-up*, this stage involves running production. Early products produced should be immediately sold in the markets to test for feedback. The supply chain strategy should be integrated into this phase for management purposes.

By applying HoQ and QFD, the linkage between customer requirements and functional specifications is embedded in the design process, ensuring that products are developed in alignment with consumer expectations. This comprehensive approach facilitates the creation of innovative, high-quality products that meet market demands effectively.

2.5. House of Quality

The House of Quality (HoQ) is a structured method used in Quality Function Deployment (QFD) to translate customer requirements into technical specifications for product design, visually representing the relationship between customer needs and design features to ensure alignment with market demands [53-57]. Key components of HoQ for beverage bottle design include customer requirements such as ergonomic design for comfort during use, ease of opening with convenient cap design, durability through material strength, aesthetic appeal to attract consumers, and environmental friendliness by utilizing recyclable or sustainable materials. These requirements inform technical specifications like material choice, which involves selecting lightweight yet durable plastics or composites, cap design options such as screw-on or flip-top, shape and size for comfortable handling, and weight considerations for portability.

The relationship matrix displays the correlation between customer requirements and technical specifications, identifying strong, moderate, or weak relationships, while competitive analysis compares design features of competing products to pinpoint strengths and weaknesses in the market. Prioritization ranks customer requirements based on their importance, guiding design decisions effectively. Applying HoQ in the design of a 330-ml beverage container ensures that customer preferences are directly addressed in product specifications, leading to a more successful market introduction and enhanced customer satisfaction.

2.6. Linear Programming

Linear programming (LP) is a mathematical technique used for optimizing a linear objective function, subject to a set of linear equality and inequality constraints. It is widely applied in various fields such as economics, engineering, military, and transportation to make decisions about resource allocation, production schedules, and other optimization problems [58-61].

In this study, we enhance the Quality Function Deployment (QFD) methodology by integrating it with linear programming. This enhancement not only considers the relationship between customer requirements and functional requirements but also considers the satisfaction levels of three distinct customer types (self-absorbed, self-confident, and self-centred) along with the associated costs. This integrated approach allows for a more detailed and comprehensive analysis, optimizing both customer satisfaction and cost-efficiency. The objective function aims to maximize the satisfaction levels of three types of customers (self-absorbed, self-confident, and self-catered). Simultaneously, the relationship matrix illustrates the correlation between customer requirements and functional requirements, while also minimizing costs. The key consideration is about applying "Linear Programming (LP)" to be a powerful tool in the design process of a bottle of water, particularly when optimizing certain aspects such as cost, material usage, or manufacturing efficiency.

3. Research Concept

Recently, after obtaining the results from the House of Quality (HoQ), the linkage and correlation between customer requirements and functional requirements have been revealed and translated into the physical design and characteristics of a new product. Although the HoQ matrix effectively maps these connections, aspects such as cost, transportation, and storage management are often only briefly mentioned or partially included, which can limit their influence on the design process. As a result, the chosen physical design specifications might lead to high investment costs if optimization between design features and cost management is not adequately integrated. Addressing these factors comprehensively is essential to align the product design with both customer needs and financial constraints, ensuring a more balanced and cost-effective outcome.

Applying the concept of Linear Programming (LP), a mathematical optimization technique widely used in economics, engineering, and management, would be beneficial. LP can plan the use of limited resources, providing quantitative support for decision-making in real-life problems. It helps optimize competitive bidding strategies for project cost selection in construction management. Additionally, LP aids in resource allocation under limited conditions, making decisions from various alternative objectives, and solving problems in fields such as transportation, logistics, and agriculture.

The design obtained from HoQ typically represents a single "master design" investigated and formed by the design team. Applying LP can open opportunities to generate alternative designs from the master root design characteristics. This allows the design team to select the optimal design from various potential product characteristics. This proposed approach leverages LP to assist product design and development (PDD) in resource allocation under limited conditions, making decisions from various alternative objectives, and solving design stage problems to obtain an optimal physical product that fits within a reasonable investment cost.

3.1. Key Contents

This study explores several key aspects of product design and development. The research emphasizes efficient and cost-effective prototyping methods for bottle design, highlighting the limitations of injection molding, which, despite its high-volume production capability, is costly and unsuitable for reshaping complex master designs. It examines the application of Linear Programming (LP), a mathematical modeling technique for optimizing business and industrial processes under various constraints. Additionally, the study underscores the importance of the House of Quality (HoQ) in translating customer requirements into precise design specifications, ensuring market alignment.

The main focus is on Product Design and Development (PDD), aiming to create effective and appealing products that meet customer expectations. The brief details of each key content are described as follows:

- *Research Focus:* Emphasizing efficient and cost-effective prototyping methods for bottle design.
- *Injection Molding:* Melts materials to form high-volume units but is costly and unsuitable for reshaping complex master designs.
- *Linear Programming:* A mathematical modeling technique in which a linear function is maximized or minimized when subjected to various constraints. This technique has been useful for guiding quantitative decisions in business planning, industrial engineering, and—to a lesser extent—in the social and physical sciences.
- *House of Quality (HoQ):* A key tool that translates customer requirements into design specifications, ensuring alignment with market needs.
- *Product Design and Development (PDD):* The overall process of creating effective and appealing products that meet customer expectations.

A. Explanation of Chosen Methodology

The proposed methodology (Fig.1), which involves LP and HoQ, is the most suitable for achieving the research objectives for several reasons:

- *Alignment with Objectives:* The goal of creating a ready-to-assemble product relies on precise fabrication and structural integrity.
- *House of Quality (HoQ):* Utilizing HoQ allows for thorough evaluation of customer requirements, translating them into technical specifications that guide the design process. This analysis is essential for ensuring the robustness and market alignment of the final prototype.
- *Linear Programming (LP) Principles:* By integrating LP principles, the methodology enhances efficiency by minimizing waste and optimizing the use of materials and resources. This approach is essential for producing sophisticated designs and maintaining high production quality.

B. Benefits of the Chosen Methodology

By applying LP and HoQ, the linkage between customer requirements and functional specifications is integrated into the design process of the 330-ml beverage container, ensuring that products are developed in alignment with consumer expectations. This comprehensive approach facilitates the creation of innovative, high-quality products that meet market demands effectively. The benefits obtained from the methods or platforms presented in this study are outlined as follows:

- *Customization and Flexibility:* The methodology allows for rapid design iterations and customizations to meet specific project requirements while maintaining high production quality.
- *Sustainability:* By incorporating a waste-to-wealth

strategy, the approach not only reduces material waste but also promotes sustainable practices in manufacturing.

- *Efficiency in Prototyping:* The combined use of LP principles, HoQ, and the Decision-Making Platform for Design Optimization significantly shortens the development cycle, enabling quicker transitions from design to physical prototype.

3.2 House of Quality (HoQ) and Quality Function Deployment (QFD) Application

House of Quality (HoQ) and Quality Function Deployment (QFD) are tools used to align customer needs with product design. HoQ is a matrix that maps customer requirements ("whats") to engineering characteristics ("hows"), helping prioritize features and identify trade-offs. QFD is a broader process that extends beyond the HoQ, guiding product development by ensuring customer needs are addressed at each stage. Together, they facilitate communication across teams and optimize design, production, and testing to ensure the final product meets customer expectations.

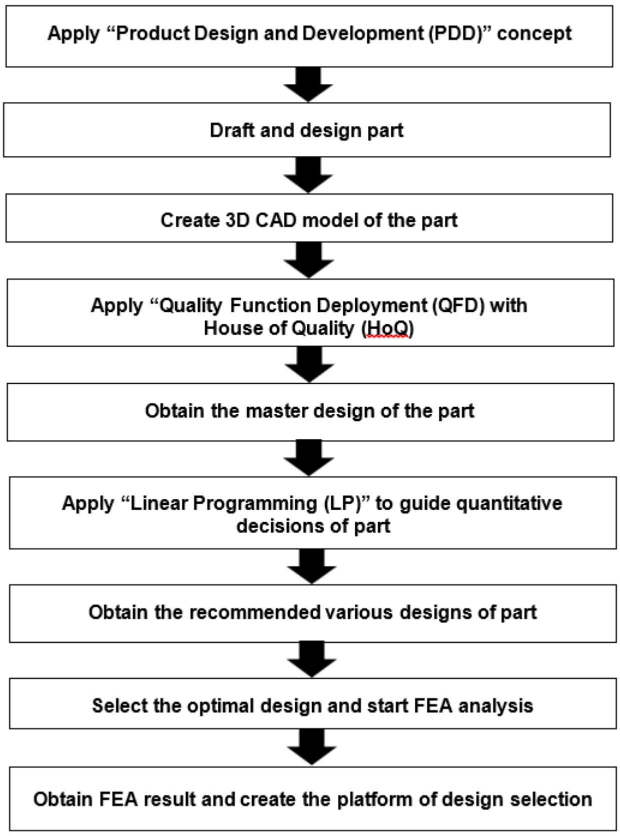

Fig. 1. Steps required for accomplishing tasks – the proposed approach.

The key is that HoQ and QFD translate customer needs into engineering specifications, ensuring that product designs align with customer expectations. This systematic approach improves product quality and reduces development time by prioritizing and addressing customer requirements throughout the development process. The key considerations of the HoQ and QFD can be expressed as:

- *Customer Requirements*: Identifying and prioritizing customer needs for the 330-ml beverage container, such as ergonomic design, ease of opening, durability, aesthetic appeal, and environmental friendliness.
- *Functional Specifications:* Translating customer requirements into technical specifications using HoQ, ensuring that design and production align with customer expectations.
- *Competitor Analysis:* Performing a competitive analysis to identify gaps and opportunities in the market, leveraging insights to refine the design and features of the beverage container.
- *Design Alternatives:* Exploring various design options and selecting those that best align with QFD analysis, ensuring the final product satisfies both functional and customer requirements.

By applying LP and HoQ methodologies, the design and development of the 330-ml small-scale container are optimized for portability, sustainability, and customer satisfaction, ensuring it meets the needs of people who need convenience while out and about and supports a successful market introduction.

4. Applications

Integrating House of Quality (HoQ) (Fig. 2) and Linear Programming (LP) in the design of a small-scale beverage container, such as a 330-ml bottle, offers multiple advantages from both design and marketing perspectives.

This approach improves overall efficiency by aligning product design with manufacturing processes, optimizing cost management, and reducing material waste. By using LP and HoQ, the design team can explore various alternatives, balancing functionality with cost-effectiveness, resulting in a more streamlined manufacturing process that reduces production costs and supports environmental sustainability.

Furthermore, this methodology helps refine the assembly process by eliminating unnecessary components, ensuring that the final product aligns with customer preferences—especially targeting younger consumers with modern, customizable, and trendy features. Incorporating sensory attributes such as taste, aroma, and visual appeal enhances consumer acceptance, ensuring the product meets current market demands while promoting sustainability goals.

The design team used data gathered from target customers aged 15-45, who primarily consume 'Soda' drinks, to define their requirements (the "What's") and applied these insights to create the product depicted in "Our Design" (Fig. 3). However, certain customer types, such as self-absorbed, self-confident, or self-centered individuals, were not considered in this initial analysis.

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Quality Function Deployment

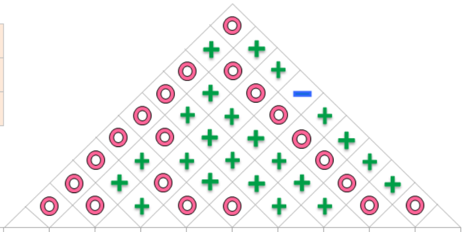
Project title:	Alternative Bottle Design
Project leader:	SR
Date:	25/1/2025

Correlation:

+	◎	−
Positive	No correlation	Negative

Relationships:

9	5	1	
Strong	Moderate	Weak	None



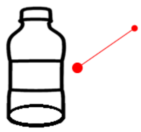
Competitive evaluation (1: low, 5: high)

	Customer Importance Rating (1: low, 5: high)	Customer Requirements - (What's) ↓ / Functional Requirements (How's) →	Color of printings	Shape of the main body	Food grade Material(Medium to high grade material)	Strength	Size of the bottle	Closure material/Cap (Thread)	Shape of closure	Thickness/Shell wall of the bottle	graphic design with univesal sign + minimal concepts	Stiffness	Weighted Score	Our designed product	Competitor rating 1 (Design A)	Competitor rating 2 (Design B)	Competitor rating 3 (Design C)
		Desired direction of improvement (↑,0,↓)	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑					
1	4	Ergonomics design of the bottle	1	9	1	5	5	1	5	1	1	1	120	5	5	2	5
2	5	Easy to open (Easy to access)		5		5	5	9	9	5		5	215	5	4	3	5
3	1	Long shelf life (main body)				9		5	5	5		9	33	4	4	4	4
4	2	Enviroment friendly			9	1		9		1		1	42	2	2	2	2
5	5	Attractive appearance	9	9	1		5	9	9	1	9		260	5	3	3	3
6	2	Easy to store (In fridge)		9	1	1	9	1	1	1		1	48	5	5	5	5
7	2	Packaging not easy to damage		5	5	9	1	5	5	1		9	80	3	3	3	3
8	3	Providing clear product information	9	5			9				9		96	4	4	4	4
9	3	Light weight		5	9	1	9	1	1	5		1	96	5	3	5	5
10	5	Affordable price	5	9	9	9	9	9	9	9	9	9	430	5	4	5	5
		Technical importance score	101	209	111	124	189	177	175	105	121	108	1420	43	37	36	41
		Importance %	7%	15%	8%	9%	13%	12%	12%	7%	9%	8%	52%				
		Priorities rank	10	1	7	5	2	3	4	9	6	8					

1: very easy, 5: very difficult

1: low, 5: high

Competitors:
- Design A: It has a slim body with four base stands.
- Design B: It is a 330-ml bottle with a smooth, straight, and minimalist large handle.
- Design C: It features a 330-ml bottle with textured grip and ergonomic contours.



Our Design: It features a 330-ml bottle with a smooth, straight grip, ergonomic contours, and a minimal design concept.

Fig. 2. House of Quality – Bottle Design Platform.

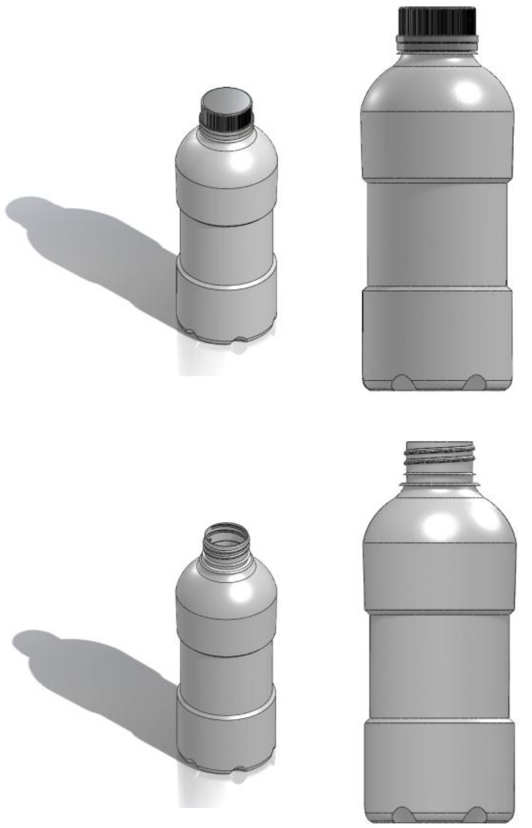


Fig. 3. Bottle designed from "HoQ" analysis – Our design.

To strengthen the design process, it would be beneficial to include these customer profiles in the evaluation. This could involve establishing a new correlation between customer requirements and functional needs to ensure a more nuanced approach. By incorporating these distinct customer types into the HoQ framework, designers can more accurately align product characteristics with diverse consumer needs, creating a more personalized and effective design solution. This would result in a product that not only appeals to a wider audience but also enhances brand loyalty and market competitiveness.

4.1. The value of satisfaction

In linear programming for product design and development, "the value of satisfaction" refers to optimizing how well a product meets user requirements and preferences. This involves incorporating satisfaction constraints—such as performance specifications, cost limits, or material standards—into the model to ensure the product adheres to essential criteria. Additionally, satisfaction can be framed as an objective to maximize, where the goal is to enhance features that significantly boost user satisfaction. By integrating these factors into the linear programming model, it is possible to balance trade-offs between competing requirements and systematically optimize the product to achieve both technical and customer satisfaction goals.

The key design of this research focuses on extracting the needs of three different types of people—self-absorbed, self-centered, and self-confident—regarding a drinking bottle. This process supports the next step, which involves an "optimization-linear programming activity" aimed at considering costs and design characteristics simultaneously.

By understanding these diverse perspectives, the research aims to create a product that balances functionality, aesthetics, and cost-effectiveness, ensuring it meets the varied preferences and demands of its target audience. From Table 1, the steps required to identify the 'value of satisfaction' can be outlined as follows:

Step ①

After identifying the lists of 'What's' (Customer Requirements), the design team has matched the type(s)of people (self-absorbed, self-centered, and self-confident) to each 'What' (per row) as indicated in Step No. ② .

Step ②

Each 'Customer Requirement' is assigned to type(s) of customers according to the concepts of product design and development and customer-centric platforms.

Step ③

The suitable 'satisfaction value' (ranging from 1 to 10), from the perspective of the assigned type(s) of customers for each 'What' (requirement on each row), will be rated on a scale for each 'How' (Functional Requirement).

After analyzing the satisfaction levels of functional versus customer requirements, the design team summarized these numerical values into descriptive terms. This transformation makes it easier to understand and communicate the information for the next stages, which are "3D virtual prototyping" and "physical prototyping." Note that numbers 1 to 9 correspond to designs numbered 1 through 9, respectively.

Rank No.4 - Design 1. For 'Self-Confident', to meet the requirement of "ergonomic design of the bottle," these functional requirements are taken into consideration: shape of the main body, food-grade material (medium to high grade), strength, size of the bottle, closure material/cap (thread), shape of closure, ease of handling, user comfort, grip texture, and overall aesthetic appeal. Additionally, the design process incorporates recent experiences from user testing and feedback to ensure that the bottle is not only functional but also intuitive and pleasant to use in various settings.

Rank No.2 - Design 2. To support the "Easy to Open (Easy to Access)" requirement for three types of users ('self-absorbed, centered, and confident people'), the following functional requirements are considered: color of the printings, shape of the main body, size of the bottle, closure material/cap (thread), and grip texture. Additionally, the design incorporates graphic design with universal signs and minimal concepts, ensuring intuitive use. The closure mechanism is designed to balance secure sealing with ease of opening, accommodating varying levels of hand strength and ability among users.

Design 3. For 'self-centered and confident people' who require a "long shelf life" for the main body of the bottle, the following functional requirements are meticulously considered: vibrant and durable color of the printings, food-grade material (medium to high grade) for safety and longevity, structural strength to withstand regular use, robust closure material/cap (thread) to ensure secure sealing, ergonomic shape of the closure for ease of use, and sufficient stiffness to maintain the bottle's integrity over time. Additionally, considerations for UV resistance and impact resistance are included to enhance the bottle's durability in various environmental conditions.

Design 4. For the "Environmentally Friendly" requirement, which is a key concern for 'self-confident people', the design team must consider several factors when creating the bottle. The primary focus is on using food-grade materials (medium to high grade) to support the functional requirements. This includes ensuring that the materials are recyclable and biodegradable, reducing environmental impact. Additionally, the production process should minimize waste and energy consumption, and the design should encourage reuse and easy disposal. The team also considers the environmental footprint of the supply chain, striving for sustainable sourcing and manufacturing practices.

Rank No.1 - Design 5. For the "Attractive Appearance" requirement from the viewpoint of 'self-absorbed and centered people', the design team must focus on several key elements. The color of the printings, the shape of the main body, and the shape of the closure are important factors. Additionally, incorporating graphic design with universal signs and minimal concepts is essential. These elements are carefully considered and integrated into the functional requirement designs to create a visually appealing and aesthetically pleasing product that resonates with these user groups.

Design 6. To support the "Easy to Store (In Fridge)" requirement from the viewpoint of 'self-confident people', several key functional requirements should be considered. These include the shape of the main body, which should be designed to fit easily into standard refrigerator compartments, maximizing space efficiency. The use of food-grade materials, preferably medium to high grade, ensures the safety and freshness of the stored contents. Additionally, the size of the bottle should be appropriate for typical refrigerator shelves, allowing for convenient storage without taking up excessive space. These considerations aim to enhance the user experience by providing a bottle that is not only easy to use but also integrates seamlessly into daily life.

Rank No.3 - Design 7. To meet the "Packaging Not Easy to Damage" requirement from the viewpoint of 'self-confident people', the design team should consider key functional requirements including the shape of the main body, food-grade material (medium to high grade), strength, size of the bottle, closure material/cap (thread), and shape of closure, ensuring durability and protection of the packaged contents. Additionally, incorporating features such as impact-resistant design and secure sealing mechanisms further enhances the packaging's ability to withstand handling and transport, meeting the expectations of self-confident consumers for reliable and damage-resistant packaging.

Design 8. From the viewpoint of 'self-absorbed and confident people', the "Providing Clear Product Information" requirement should be a key consideration in the functional design platform. This includes focusing on the color of printings and incorporating graphic design with universal signs and minimal concepts. These elements play an important role in ensuring that product information is easily accessible, visually appealing, and effectively communicates key details to consumers. Additionally, clear and concise labeling enhances the overall user experience, aligning with the expectations of self-absorbed and confident people for products that meet their informational needs in a straightforward and visually appealing manner.

Design 9. "Lightweight" is a popular requirement needed by 'three types of people'. In addition to considering the color of printings, shape of the main body, size of the bottle, closure material/cap (thread), and graphic design with universal sign plus minimal concepts as functional requirements, the design team also focuses on materials that are both lightweight and durable. The packaging is designed to be easy to carry and handle, catering to the convenience and preferences of the target user groups. Additionally, the use of innovative lightweight materials and streamlined design elements further enhances the product's appeal and usability, meeting the expectations of self-absorbed, centered, and confident individuals for lightweight, functional, and aesthetically pleasing packaging solutions.

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Table 1. The Value of Satisfaction – Functional Requirements versus Customer Requirements.

Vij Step ②	No.	Functional Requirements - (How's) → Step ③ Customer Requirements - (What's) ↓ Step ①	Color of printings	Shape of the main body	Food grade Material (Medium to high grade material)	Strength	Size of the bottle	Closure material/Cap (Thread)	Shape of closure	Thickness/ Shell wall of the bottle	Graphic design with universal sign + minimal concepts	Stiffness
Self-Confident	1	Ergonomics design of the bottle	0	10	9	8	7	7	7	5	6	6
All	2	Easy to open (Easy to access)	7	8	6	6	9	7	6	5	7	6
Self-Centered / Confident	3	Long shelf life (Main body)	8	0	7	8	2	7	7	6	0	8
Self-Confident	4	Environment friendly	0	5	9	6	6	6	6	5	6	6
Self-Absorbed / Centered	5	Attractive appearance	10	10	3	0	6	5	7	2	10	0
Self-Confident	6	Easy to store (In fridge)	0	8	7	0	8	5	5	3	1	0
Self-Confident	7	Packaging not easy to damage	0	10	9	8	7	7	7	5	6	6
Self-Absorbed / Confident	8	Providing clear product information	8	5	5	6	6	5	5	5	9	5
All	9	Light weight	7	8	6	6	9	7	6	5	7	6

4.2. Design Considerations – Recommended Bottle Design

Based on the consensus of the research team, nine design characteristics of bottles were analyzed according to different types of people (as determined from questionnaire responses and direct interviews). Among these characteristics, four were identified as best fitting for the manufacturing and assembly platform. These four characteristics are recommended as master models for creating guidelines (Table 2) to optimize the design and linear programming process.

Rank No.1 - For the *'Attractive Appearance'* requirement, focus on print color, body shape, and closure shape. Incorporate universal graphics and minimal concepts to appeal to *'self-absorbed and centered'* users.

Rank No.2 - For the *'Easy to Open'* requirement, key considerations for *'self-absorbed, centered, and confident' users* include print color, body shape, bottle size, closure material, and grip texture. The design features universal graphics and minimal concepts for straightforward use, with a closure mechanism balancing secure sealing and ease of opening for users with varying hand strength and ability.

Rank No.3 - For *'Packaging Not Easy to Damage,'* focus on body shape, high-grade material, strength, size, and closure design. Ensure impact resistance and secure sealing for durability and protection, meeting *'self-confident'* users' expectations.

Rank No.4 - For *'Self-Confident,'* focus on ergonomic design with considerations for body shape, food-grade material, strength, size, closure, grip texture, ease of handling, user comfort, and aesthetic appeal. Incorporate user feedback to ensure the bottle is both functional and pleasant to use.

Table 2. Design example for each (Rank) Key consideration.

Rank	Key Considerations	Picture
1	**Print color**, **an interesting and niche body shape**, and closure shape. Incorporate universal graphics and minimal concepts for **'self-absorbed and centered' users.**	
2	**Print color, body shape,** bottle size, closure material, grip texture. Features universal graphics and minimal concepts, **balancing secure sealing and ease of opening** for **'self-absorbed, centered, and confident' users.**	
3	Body shape, **high-grade material, strength,** size, closure design. Ensure impact resistance and secure sealing for **durability and protection**, meeting **'self-confident'** users' expectations.	
4	**Prioritize ergonomic design**, evaluating **body shape**, material, **strength**, size, closure, grip, **comfort**, and aesthetics. Ensure user feedback is integrated for **functionality and appeal** for **'self-confident'** people.	

4.3. Optimization and Linear Programming Considerations

In designing the small-scale beverage container (330-ml), incorporating optimization techniques and linear programming plays a critical role in achieving a balance between design features and cost management. Insights from the House of Quality (HoQ) have guided the alignment of customer needs with product specifications; however, the relationship between design features and cost-related factors, such as transportation and storage, is often inadequately addressed.

To *improve this alignment*, optimization methods and linear programming are used to evaluate and adjust design elements, ensuring they meet both functional requirements and cost limitations. These techniques enable a more refined design process by incorporating detailed cost analysis, ensuring that the final product strikes the ideal balance between performance, quality, and economic feasibility. This approach not only allows for efficient resource allocation and cost reduction but also facilitates the development of a high-quality product that is both market-ready and cost-effective.

From *a marketing perspective*, optimizing design and cost ensures that the product is competitively priced while maintaining premium quality. By addressing factors like efficient transportation and storage, the product can also appeal to retailers, further improving its marketability. Moreover, incorporating design features that appeal to key consumer segments—such as sustainability, aesthetic appeal, and convenience—adds value that aligns with what target people want. This integrated approach supports the development of a product that not only meets the functional needs of customers but also fits with broader market demands, enhancing its success in a competitive marketplace. Thus, *the design team* has developed guidelines for applying Linear Programming (LP) to this small-scale beverage container project, with key components of this approach explained in the following sub-sections.

A. Objective Definition

To define the objective function, the first step is to determine what needs to be optimized. For example, the goal might be to minimize production costs while ensuring the bottle maintains its structural integrity and aesthetic appeal.

B. Design Variables

Identifying the variables that affect the design is important. For a water bottle, these variables include the volume of the bottle, the thickness of the material, shape parameters such as height and diameter, and the type and properties of the material used.

C. Constraints

Constraints should be established based on design requirements and limitations. These constraints may include the minimum and maximum volume capacity, maximum weight, material strength and durability requirements, manufacturing limitations such as mold dimensions and machine capabilities, cost constraints, and environmental considerations like using recyclable materials.

4.4 Formulating the Linear Programming Model

In this section, the Linear Programming (LP) model will be formulated to optimize the bottle design. A structured approach will be provided for decision-making by identifying key variables, constraints, and objective functions. Design requirements will be translated into a mathematical framework, allowing different design options to be systematically evaluated for optimal balance between performance and cost-efficiency. The objective function will be defined, constraints established, and variables impacting the design identified, all of which are important for the development of a feasible and effective design solution.

A. Objective Function Example:

$$Minimize\ cost\ C = c_1x_1 + c_2x_2 + c_3x_3 + \cdots + c_nx_n$$

where x_i are the design variables (e.g., material thickness, volume) and

c_i are the cost coefficients.

B. Constraints Example:

- Volume constraint: $V = \pi r^2 h \geq V_{min}$
- Weight constraint: $W = \rho V \leq W_{max}$
- Material strength constraint: $S \geq S_{required}$
- Cost constraint: $C \leq C_{max}$
- Environmental constraint: $E \leq E_{max}$

C. Solving the LP Model

To solve the formulated linear programming (LP) model, appropriate LP solvers or software such as MATLAB, Python with PuLP, or LINGO should be used to obtain the optimal values of the design variables. Excel Solver also serves as a powerful and accessible tool for addressing linear programming and optimization problems. It enables users to define an objective function, specify decision variables and constraints, and efficiently determine the optimal solution [62–63].

D. Implementation and Iteration

- Implement the solution in the design prototype.
- Test and iterate based on real-world performance and feedback.

Objective: Minimize the cost of material while maintaining structural integrity.

Variables:

- x_1 : Thickness of the bottle wall
- x_2 : Height of the bottle
- x_3 : Diameter of the bottle base

Objective Function:

- $Minimize\ cost\ C = c_1x_1 + c_2x_2 + c_3x_3$

Constraints:

- Volume constraint:
$$V = \pi(x_3/2)^2 x_2 \geq 500\ ml$$
- Material constraint:
$$S = Material\ Strength \geq S_{required}$$
- Weight constraint:
$$W = \rho V \leq 50\ g$$
- Cost constraint:
$$C \leq \$0.50$$

By applying Linear Programming (LP) to the design of a water bottle, a systematic approach to optimizing multiple design criteria is ensured. A balanced trade-off between cost, material usage, and performance is achieved, ultimately leading to a more efficient and effective design process.

4.5. Integrating Linear Programming and House of Quality

Based on the concept outlined in the previous section, the design team applied Linear Programming (LP) to the case study of designing a 330-ml beverage bottle. Fig. 4 to 8 present data incorporating key optimization components. These components include:

- **Vij** is Satisfaction level
- **Rij** is Relationship among factors
- **Sij** is Combination of Vij and Rij
- **Cij** is Cost ratio of operation or activity
- **Xij** is Analysis result

The comparison between Sij and Cij determines whether Xij is filled with 1, indicating that if Cij is less than Sij, the corresponding cell in the correlation matrix between customer requirements (row) and engineering viewpoints (column) is marked. This process ensures that the most cost-effective and satisfying design solutions are identified. The results help in refining the design to balance performance and cost effectively.

Model Components

- x_{ij} : Binary decision variable (0 or 1) indicating whether the j-th functional requirement is implemented for the i-th customer requirement.
- V_{ij}: Initial satisfaction value for the i-th customer requirement due to the j-th functional requirement.
- R_{ij} : Additional satisfaction or relationship

strength between the i-th customer requirement and the j-th functional requirement upon implementation.

- C_{ij} : Cost ratio associated with implementing the j-th functional requirement for the i-th customer requirement.
- S_{ij} : Total satisfaction score for the i-th customer requirement due to the j-th functional requirement.
- n : Number of customer requirements (9).
- m : Number of functional requirements (10).

Satisfaction Calculation

For each combination of customer requirement i and functional requirement j, the total satisfaction score S_{ij} is defined as:

$$S_{ij} = V_{ij} + R_{ij}$$

Objective Function

The objective function aims to maximize the total satisfaction score, Z, minus the total cost, incorporating the specific satisfaction and cost associated with each decision variable.

$$Z = \sum_{i=1}^{n}\sum_{j=1}^{m} S_{ij}x_{ij} - \sum_{i=1}^{n}\sum_{j=1}^{m} C_{ij}x_{ij}$$

Mathematical Model

$$Maximize\ Z = \sum_{i=1}^{n}\sum_{j=1}^{m} (V_{ij} + R_{ij})x_{ij} - \sum_{i=1}^{n}\sum_{j=1}^{m} C_{ij}x_{ij}$$

Subject to:

Binary Decision Variables:

$$x_{ij} \in \{0,1\}, \forall_i = 1, \dots, n, \qquad \forall_j = 1, \dots, m$$

Budget Constraint (if applicable):

$$\sum_{i=1}^{n}\sum_{j=1}^{m} C_{ij}x_{ij} \le B$$

Analysis

In this refined model:

- **Satisfaction Matrix** S : This matrix now fully captures the total satisfaction from both initial satisfaction and additional benefits from implementing functional requirements.
- **Cost Matrix** C: Each element C_{ij} accounts for the specific cost associated with implementing a functional requirement for a customer requirement.
- **Decision Variables** x_{ij} : These determine the implementation of each functional requirement for each customer requirement, thereby affecting both satisfaction and cost.

The model aims to find the optimal set of decisions x_{ij} that maximizes the overall satisfaction while minimizing costs and possibly staying within a budget constraint. This setup allows for a detailed and specific optimization process, ensuring that all aspects of customer satisfaction and cost are accounted for in the decision-making process. This formulation enables a comprehensive and precise optimization process, ensuring that all relevant aspects of customer needs and cost efficiency are systematically addressed in the decision-making framework.

Based on the findings shown in Fig. 8 (the analysis results), the design team has combined both functional and customer requirements, providing the following key insights:

- The concept of "*Graphic design with universal symbols and minimalistic features*" stands out as the top priority, indicating its high value to customers. This concept focuses more on addressing the "What" of customer needs from an engineering design perspective than other functional aspects.
- *Strength, bottle size, and closure material (thread)* also rank highly, emphasizing their importance in fulfilling customer demands.
- The *color of prints, body shape, closure design, and stiffness* are of moderate importance, whereas food-grade materials (medium to high quality) and bottle wall thickness are seen as less critical, suggesting these elements have a smaller impact on customer satisfaction.

Vij		Functional Requirements (How's) → / Customer Requirements - (What's) ↓	1 Color of printings	2 Shape of the main body	3 Food grade Material(Medium to high grade material)	4 Strength	5 Size of the bottle	6 Closure material/Cap (Thread)	7 Shape of closure	8 Thickness/Shell wall of the bottle	9 Graphic design with universal sign + minimal concepts	10 Stiffness
	1	Ergonomics design of the bottle	0	10	9	8	7	7	7	5	6	6
	2	Easy to open (Easy to access)	7	8	6	6	9	7	6	5	7	6
	3	Long shelf life (main body)	8	0	7	8	2	7	7	6	0	8
	4	Enviroment friendly	0	5	9	6	6	6	6	5	6	6
	5	Attractive appearance	10	10	3	0	6	5	7	2	10	0
	6	Easy to store (In fridge)	0	8	7	0	8	5	5	3	1	0
	7	Packaging not easy to damage	0	10	9	8	7	7	7	5	6	6
	8	Providing clear product information	8	5	5	6	6	5	5	5	9	5
	9	Light weight	7	8	6	6	9	7	6	5	7	6

Fig. 4. Satisfaction values from the perspectives of three customer types.

Rij		Functional Requirements (How's) → / Customer Requirements - (What's) ↓	1 Color of printings	2 Shape of the main body	3 Food grade Material(Medium to high grade material)	4 Strength	5 Size of the bottle	6 Closure material/Cap (Thread)	7 Shape of closure	8 Thickness/Shell wall of the bottle	9 Graphic design with universal sign + minimal concepts	10 Stiffness
	1	Ergonomics design of the bottle	1	10	1	5	5	1	5	1	1	1
	2	Easy to open (Easy to access)		5		5	5	10	10	5		5
	3	Long shelf life (main body)				10		5	5	5		10
	4	Enviroment friendly			10	1		10		1		1
	5	Attractive appearance	10	10	1		5	10	10	1	10	
	6	Easy to store (In fridge)		10	1	1	10	1	1	1		1
	7	Packaging not easy to damage		5	5	10	5	5	5	1		10
	8	Providing clear product information	10	5			10				10	
	9	Light weight		5	10	1	10	1	1	5		1

Fig. 5. The relationship between "Whats" and "Hows".

Sij		Functional Requirements (How's) → / Customer Requirements - (What's) ↓	1 Color of printings	2 Shape of the main body	3 Food grade Material(Medium to high grade material)	4 Strength	5 Size of the bottle	6 Closure material/Cap (Thread)	7 Shape of closure	8 Thickness/Shell wall of the bottle	9 Graphic design with universal sign + minimal concepts	10 Stiffness
	1	Ergonomics design of the bottle	1	20	10	13	12	8	12	6	7	7
	2	Easy to open (Easy to access)	7	13	6	11	14	17	16	10	7	11
	3	Long shelf life (main body)	8	0	7	18	2	12	12	11	0	18
	4	Enviroment friendly	0	5	19	7	6	16	6	6	6	7
	5	Attractive appearance	20	20	4	0	11	15	17	3	20	0
	6	Easy to store (In fridge)	0	18	8	1	18	6	6	4	1	1
	7	Packaging not easy to damage	0	15	14	18	12	12	12	6	6	16
	8	Providing clear product information	18	10	5	6	16	5	5	5	19	5
	9	Light weight	7	13	16	7	19	8	7	10	7	7

Fig. 6. The combination of "Customer requirement (i)" and "Functional requirement (j)".

Cij		Functional Requirements (How's) → / Customer Requirements - (What's) ↓	1 Color of printings	2 Shape of the main body	3 Food grade Material(Medium to high grade material)	4 Strength	5 Size of the bottle	6 Closure material/Cap (Thread)	7 Shape of closure	8 Thickness/Shell wall of the bottle	9 Graphic design with universal sign + minimal concepts	10 Stiffness
	1	Ergonomics design of the bottle	2	18	10	12	14	13	14	13	2	12
	2	Easy to open (Easy to access)	2	16	12	13	13	13	13	13	0	12
	3	Long shelf life (main body)	0	0	12	16	4	13	13	13	0	16
	4	Enviroment friendly	6	6	14	6	6	14	6	12	0	6
	5	Attractive appearance	14	18	6	0	10	14	14	6	18	0
	6	Easy to store (In fridge)	0	14	12	2	6	4	8	6	0	2
	7	Packaging not easy to damage	0	14	13	16	4	13	12	10	0	16
	8	Providing clear product information	14	14	0	0	14	0	0	0	14	0
	9	Light weight	0	14	16	4	0	2	2	2	0	4

Fig. 7. The specific cost ratio associated with implementing a functional requirement for a customer requirement.

Xij		Functional Requirements (How's) → / Customer Requirements - (What's) ↓	1 Color of printings	2 Shape of the main body	3 Food grade Material(Medium to high grade material)	4 Strength	5 Size of the bottle	6 Closure material/Cap (Thread)	7 Shape of closure	8 Thickness/Shell wall of the bottle	9 Graphic design with universal sign + minimal concepts	10 Stiffness
	1	Ergonomics design of the bottle	0	1	0	1	0	0	0	0	1	0
	2	Easy to open (Easy to access)	1	0	0	0	1	1	1	0	1	0
	3	Long shelf life (main body)	1	0	0	1	0	0	0	0	0	1
	4	Enviroment friendly	0	0	1	1	0	1	0	0	1	1
	5	Attractive appearance	1	1	0	0	1	1	1	0	1	0
	6	Easy to store (In fridge)	0	1	0	0	1	1	0	0	1	0
	7	Packaging not easy to damage	0	1	1	1	1	0	0	0	1	0
	8	Providing clear product information	1	0	1	1	1	1	1	1	1	1
	9	Light weight	1	0	0	1	1	1	1	1	1	1
		Sum	5	4	3	6	6	6	4	2	8	4

Fig. 8. The binary decision variable (the analysis results).

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This prioritization helps the design team focus on the most important features that align with customer expectations. Further analysis of the results from Xij was performed by comparing cost (Cij) and total satisfaction (Sij), revealing key factors that assist in reducing both costs and design time during the design, development, and manufacturing phases.

Significantly, the analysis revealed that thickness/shell wall was identified as one of the least important factors, likely influenced by cost and satisfaction considerations. However, if customers continue to raise concerns about water spillage during cap opening or drinking, bottle thickness and shell wall must become a primary focus for further consideration and refinement.

4.6. Discussion

Key Points of the Proposed Method

In product design and development, numerical optimization methods help identify the best design parameters (e.g., shape, size, material properties) under various constraints (e.g., cost, strength, performance). These methods use numerical approximation and are widely applied in engineering, physics, and product design to solve problems related to optimization, differential equations, systems of equations, integration, interpolation, and simulation. The proposed model combines classical linear programming with QFD-inspired satisfaction and cost matrices—making it a hybrid of deterministic optimization and decision-analysis frameworks. While some methods focus only on cost, weight, or physical/mechanical properties (like specialized mathematical optimizations or structural design techniques), others such as Fuzzy QFD or Stochastic Dominance integrate softer, customer-facing variables—similar in spirit to the binary matrix of customer satisfaction used here. Thus, the proposed model demonstrates a practical and robust numerical optimization technique designed for product configuration problems that involve both quantitative and qualitative design factors, making it ideal for practical product development.

B. Assessing Classical LP for Product Design Decisions

The classic LP model is suitable for preliminary design optimization, especially when the goal is to minimize cost under well-defined physical constraints. It is efficient, simple, and accessible. However, it does not account for customer preferences or qualitative trade-offs, which are essential for user-centered product design. The QFD-based LP model offers a more comprehensive, customer-focused alternative, suitable for refining designs when customer satisfaction metrics are available. It is particularly valuable when balancing engineering features against perceived value and implementation costs.

The proposed approach utilizes classic Linear Programming (LP) to optimize the design of a 330-ml beverage bottle by minimizing material cost while satisfying functional constraints such as volume, weight, strength, and environmental limits. LP is applied in two distinct but complementary phases: (1) a cost-based continuous model where variables such as wall thickness, bottle height, and diameter are adjusted to minimize total cost, and (2) a binary satisfaction-cost trade-off model where decision variables (Xij) represent the inclusion of specific functional requirements for each customer need. This second model maximizes total satisfaction (Vij + Rij) minus cost (Cij) under a possible budget constraint. Together, these models enable systematic decision-making in balancing engineering feasibility, cost-efficiency, and customer satisfaction. Compared to more advanced nonlinear or heuristic optimization techniques, the classic LP formulation remains a suitable and efficient choice due to its transparency, ease of implementation (e.g., in Excel Solver, Python PuLP, or LINGO), and capability to yield actionable insights for early-stage product design. However, while LP provides structure and computational simplicity, it may lack flexibility in capturing complex, non-linear interactions or uncertain real-world conditions that could benefit from multi-objective or fuzzy optimization methods. Moreover, the proposed model integrates classical linear programming with QFD-inspired satisfaction and cost matrices, forming a hybrid approach that combines deterministic optimization with decision-analysis frameworks.

Whereas some optimization methods emphasize quantitative factors such as cost, weight, or mechanical properties (e.g., Trust Region or Structural Optimization), others—like Fuzzy QFD and Stochastic Dominance—incorporate qualitative, customer-centric variables. This aligns conceptually with your use of a binary matrix to evaluate customer satisfaction.

What distinguishes the proposed approach is its balanced treatment of both numerical and qualitative design elements—such as volume, cost, satisfaction, and material strength—making it particularly well-suited for practical, constraint-driven product development.

C. Other Models

Table 3 presents a comparison of numerical optimization methods used in product design and development. To provide more detailed and precise information about the proposed approach and alternative models, Table 4 is included and discussed. This facilitates the design team's understanding of key aspects essential for shaping the design and development stages in subsequent processes. The criteria considered include: *Type of Variables, Objective, Complexity, Customer-Centric Focus, Suitability for Early Design, Real-World Accuracy,* and *Tools Required.*

<u>Nonlinear Models</u>
Definition: These are mathematical models where the relationship between variables is not a straight line (i.e., not linear). They can more accurately represent complex

real-world problems, including user behavior or satisfaction.

User-Centric Relevance: They capture complex and dynamic user interactions with a system or product. Often used in behavior modeling, such as predicting user satisfaction based on multiple interacting features (e.g., usability, comfort, efficiency). Nonlinear regression or optimization helps personalize products/services by better representing real user experiences instead of assuming uniformity.

- GA (Genetic Algorithms)
Definition: GA is a nature-inspired optimization technique that mimics biological evolution. It searches for the best solution by iteratively selecting, combining, and mutating candidate solutions.
User-Centric Relevance: this supports multi-objective optimization, allowing designers to balance trade-offs such as cost vs. comfort or speed vs. ease-of-use—key considerations for diverse user needs. This can be used to generate customized design configurations or product options based on individual user preferences or feedback loops. Particularly, this is very useful when user constraints are nonlinear, qualitative, or uncertain, such as subjective comfort levels or visual appeal.

- MCDA (Multi-Criteria Decision Analysis)
Definition: A structured framework to evaluate multiple conflicting criteria in decision-making processes. It includes methods like AHP (Analytic Hierarchy Process).
User-Centric Relevance: this incorporates user preferences explicitly by assigning weights to criteria based on surveys, expert input, or stakeholder consultation. It helps prioritize features or solutions that are most important to the user. This promotes transparency in design choices, ensuring that trade-offs reflect actual user values rather than technical convenience alone. Especially, it is useful in participatory design processes where end-users, designers, and decision-makers collaborate.

Table 3. Comparison of Numerical Optimization Methods in Product Design and Development.

Title / Method	Optimization Type	Key Strengths	Key Limitations	Application Focus
Linear Programming-Based QFD in Fuzzy Environment [64]	Linear Programming + Fuzzy Logic	Effectively models uncertain preferences; guides sustainable decisions	Requires detailed, uncertain data; complex setup	Sustainable apparel retailing strategy
Fuzzy Optimization for New Product Design [65]	Fuzzy Set Theory + QFD	Captures vague customer needs; integrates them into product design	Computationally heavy; harder for non-experts	New product concept development under ambiguity
An integrated quality-function-deployment and stochastic-dominance-based decision-making approach [66]	QFD + Stochastic Dominance (Multi-Criteria + Probabilistic Optimization)	Risk-sensitive decisions under uncertainty; useful for trade-offs	Requires probabilistic estimates; model complexity	Product selection with performance uncertainty
Uniform Strength Design in Frame Structures [67]	Structural Optimization (Deterministic)	Targets mechanical strength, reliability, and efficiency	Ignores soft attributes like user preferences	Engineering of safe, lightweight structures
Trust Region Methods [68]	Nonlinear Constrained Optimization	Robust for nonlinear models; finds local optima reliably	Needs good initial guess; sensitive to tuning	Cost, weight, or reliability optimization in engineering
General Numerical Optimization [69]	Gradient-Based Methods	Broad use cases; well-grounded theoretically	May get trapped in local minima; tuning needed	Energy-saving design, cost-effective component choices
Nature-Inspired Algorithms [70]	Metaheuristics (e.g., Genetic Algorithms, Particle Swarm Optimization - PSO)	Solves complex, multi-objective problems well	Less predictable results; may require large computation	Material selection, ergonomic layout, feature optimization
Genetic Algorithm Applications Review [71]	Genetic Algorithm (GA)	Efficient for large solution spaces; supports creative exploration	Needs careful tuning; may be slow to converge	Product layout, visual design, packaging refinement
∗ Proposed LP + QFD-Based Model for Bottle Design	**Linear Programming + Binary QFD Model**	**Balances cost and satisfaction precisely; structured and explainable; uses real product data**	**Requires accurate satisfaction/cost data; binary model simplifies real-world nuance**	**330-ml bottle optimization: cost, strength, weight, customer preferences integrated**

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Table 4. Key aspects essential for shaping the design and development stages in subsequent processes.

Key Aspect	Classic LP	QFD-Based Binary LP (The proposed approach)	Other Models (e.g., Nonlinear/*GA/*MCDA)
Type of Variables	Continuous	Binary	Mixed (continuous/discrete)
Objective	Minimize cost	Maximize satisfaction minus cost	Multiple objectives (e.g., Pareto optimization)
Complexity	Low	Moderate–High	High
Customer-Centric	No	Yes	Varies (depends on technique)
Suitability for Early Design	High	Moderate	Low to Moderate
Real-World Accuracy	Moderate (may miss nonlinearities)	Moderate (depends on quality of Vij/Rij)	High (e.g., Nonlinear Programming, Evolutionary Alg.)
Tools Required	Excel, PuLP, MATLAB	Specialized LP solvers, QFD matrices	GA solvers, MCDA tools, simulation

Note:
GA: Genetic Algorithm
MCDA: Multi-Criteria Decision Analysis (sometimes also called Multi-Criteria Decision-Making (MCDM))
These methods are often used in product design and optimization when multiple objectives or complex, nonlinear relationships need to be considered.

C. Recommendation

It is advisable to adopt Classical Linear Programming (LP) during the early stages of product design and development. This approach offers a straightforward and efficient way to assess initial feasibility, allocate resources, and establish baseline cost estimations. Its simplicity makes it well-suited for early decision-making when the factors involved are relatively clear and easy to manage. As the design process advances and customer expectations become more detailed, it is recommended to integrate more advanced techniques, such as Quality Function Deployment (QFD)-based LP or multi-objective optimization models. These methods allow designers to consider multiple important factors—such as cost, product performance, ease of manufacturing, and customer satisfaction—at the same time, leading to more balanced and customer-focused results.

In situations where the relationships between design variables are more complicated or not straightforward, Nonlinear Programming (NLP) or problem-solving techniques like Genetic Algorithms (GA) should be used. These approaches are especially useful for solving challenging problems, helping designers explore more possibilities, understand trade-offs, and find the best possible solutions when simpler methods are not enough.

Using these optimization techniques at the right time—based on the stage of design and how complex the situation is—can improve the quality of decisions, reduce trial-and-error work, and support a stronger, more flexible, and customer-oriented product development process.

5. Finite Element Analysis (FEA)

To address this, a thorough evaluation of the bottle's thickness and shell wall, alongside closure twist force analysis, using virtual simulations can identify potential issues. This enables the design team to refine the bottle's safety and functionality. To ensure the design meets all necessary standards, we employ Finite Element Analysis (FEA) [72-75], a powerful tool for optimizing and fine-tuning the design. Using Finite Element Analysis (FEA) helps evaluate the strength of a 330-ml plastic bottle by simulating and analyzing different stress factors. The process involves breaking the bottle's design into smaller parts, making it easier to study how the material behaves under various conditions. Key steps (Table 5) include checking the strength of the bottle, especially around the body and cap, with attention to how the cap moves. FEA helps predict how the bottle will deform, find areas where stress builds up, and ensure the bottle will last and perform well. It is essential in improving the design to handle outside pressure, reduce the risk of failure, and maintain safety and function.

Table 5. Activities required for FEA.

Activity	Description
1. 3D Model Development	It is important to begin by creating a detailed 3D representation of the bottle, including both the body and cap. The model must accurately capture all design elements, dimensions, and material properties, ensuring precise simulation results.
2. Defining Material Properties	It is essential to assign realistic material characteristics, such as elasticity, tensile strength, and yield strength of the plastic. These properties help simulate how the bottle will respond under different real-world conditions, contributing to accurate performance predictions.
3. Applying Loads and Constraints	It is necessary to apply appropriate loads and boundary conditions to the model. Body Stress: Apply internal pressure to simulate the effect of liquid inside the bottle, affecting the bottle walls. Cap Stress: Simulate forces during cap rotation, such as torque and shear forces acting on the cap and threads.
4. Mesh Generation	It is key to create a finite element mesh that divides the model into smaller sections for easier analysis. The mesh should be more refined in areas of high stress, such as around the cap threads and body junctions, to improve result accuracy.
5. FEA Simulation Execution	It is necessary to perform the FEA simulation to assess stress distribution, deformation, and potential failure points under the applied loads. This step provides critical insight into the bottle's structural behavior in real-world conditions.
6. Analyzing Results	It is vital to analyze the simulation results carefully to identify areas of high stress and deformation. The goal is to ensure the bottle's design can withstand applied forces without failure, maintaining both safety and performance.
7. Design Refinement	It is important to refine the design based on FEA results to enhance strength, optimize durability, and minimize material stress. Possible improvements could involve modifying the body thickness, redesigning the cap threads, or selecting better materials for improved performance.
8. Validation through Physical Testing	It is highly recommended to validate the FEA results by performing physical tests on a prototype. This ensures that the simulated behavior aligns with actual performance and confirms the reliability of the design.

6. Applications

In 2025, several major marketing trends are influencing how small beverage containers like the 330-ml bottle are designed and promoted. People today want products that feel personal, are good for the planet, and stand out visually. To meet these expectations, product development needs to focus on sustainability, unique looks, and smart promotion. For example, using eco-friendly materials fits well with growing concern for the environment, while simple, eye-catching packaging helps attract attention in stores and online. Personalization is also key—bottles can be designed in different styles or printed with names or fun messages to match people's preferences. Short-form videos on platforms like TikTok and Instagram are now a main way to show off new products, and teaming up with smaller online influencers helps brands reach niche markets with higher trust and engagement. Companies are also using customer data, such as feedback and preferences, to shape better products and build stronger relationships. For the 330-ml drink bottle, focusing on clear labeling, reusable or recyclable packaging, and fun, modern design helps it stand out. These strategies, when combined with current marketing trends, improve how well the product connects with people and increase its chances of success in today's fast-moving and competitive market.

The objective of this experiment is to evaluate the structural integrity of a proposed plastic water bottle design made from Polyethylene Terephthalate (PET), a material widely used as primary packaging in non-alcoholic beverage products [76-77]. The analysis focuses on the application of torque to the bottle cap to identify potential structural issues prior to manufacturing and to ensure the bottle's strength and durability under typical usage conditions. Finite Element Analysis (FEA) was performed using SolidWorks software on the proposed design (Fig. 9–10). A torque of 1 N·m was applied to the bottle cap, while the bottle body was fixed in place (Fig. 11), simulating the action of twisting the cap during opening.

A. Results from FEA

The FEA results showed that the lower section of the cap, where it connects to the security band, experiences noticeable deformation when torque is applied, as illustrated in Fig. 12. The security band is a ring that stays on the bottle neck after the cap is removed, acting as a clear sign that the bottle has been opened and helping to keep the cap secure during shipping and handling. The band (shown in Fig. 10) is integrated with the cap through the injection molding process and often includes small perforations that make it easier to break apart when the cap is twisted. This large deformation in the cap's lower section reveals that this area is likely to be affected by twisting forces. To improve the durability and performance of the bottle cap, the following adjustments are recommended:

- *Increase Thickness:* Strengthening the area at the lower part of the cap where it meets the security band will increase the cap's overall strength, preventing deformation and maintaining its shape under stress.
- *Material Enhancement:* Using a stronger plastic material for the cap can significantly boost its ability to resist twisting forces, making it more durable during use.

While the security band is designed with perforations to allow it to break easily when the cap is twisted, it must also be strong enough to keep the cap securely in place. The thin plastic connection between the cap and the security band deforms too much during the twisting motion, as seen in Figs. 11-12, which may lead to the connection breaking prematurely. By addressing these critical areas, the bottle cap can be made more robust, ensuring it performs reliably throughout its lifecycle. Increasing the cap's thickness and selecting a stronger material will help prevent failures during regular use, making the cap more resilient to the forces it will encounter in everyday handling and transportation. These adjustments will contribute to a bottle cap that is both strong and functional, offering greater durability and improved performance.

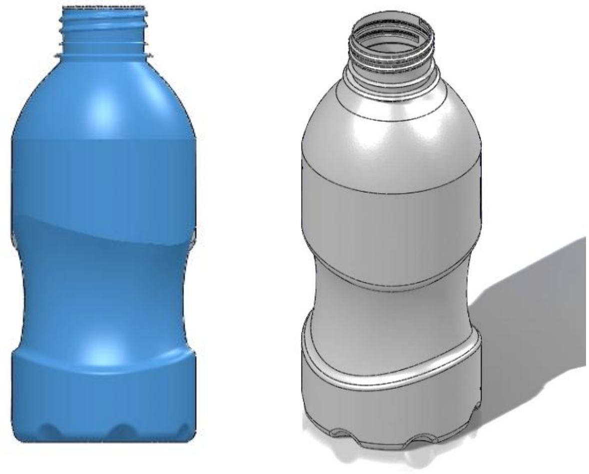

Fig. 9. 3D model of the 330-ml bottle master design.

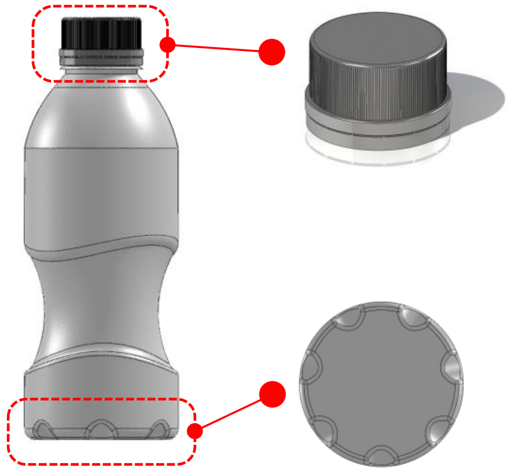

Fig. 10. Key components of the 330-ml bottle master design – bottom area and cap.

The Finite Element Analysis (FEA) results offer the design team valuable insights into the twisting forces required to open the bottle cap. A critical focus is the connection point between the cap and the tamper-evident band, as its dimensions directly influence the torque needed for opening. This study emphasizes accessibility for elderly users, who often struggle to open standard caps independently. Individuals aged 70 and above can typically exert only 0.59 to 0.7 Nm of torque [78]. This limited strength makes it challenging for them to open caps, particularly those with tamper-evident features.

Balancing product safety with user-friendliness is essential in ergonomic bottle cap design. Various connection sizes between the cap and tamper-evident band were evaluated to determine the torque required to break the seal. One tested design featured a connection size of 0.66 mm × 0.51 mm. In the FEA simulation, the cap material was High-Density Polyethylene (HDPE) with a yield strength of 21.9 MPa. Results indicated that a torque of 0.6 Nm was insufficient to break the connection, confirming that elderly users would likely need assistance.

This design required between 1.0 and 1.5 Nm to disengage the band.

To enhance accessibility by making the cap easier to open, an alternative design was tested using the same material but with a reduced connection size of 0.45 mm × 0.51 mm. The simulation results showed that this version could be opened with a torque of 0.6 Nm—within the range that elderly users can typically apply. The comparative results are illustrated in Fig. 13 to 14.

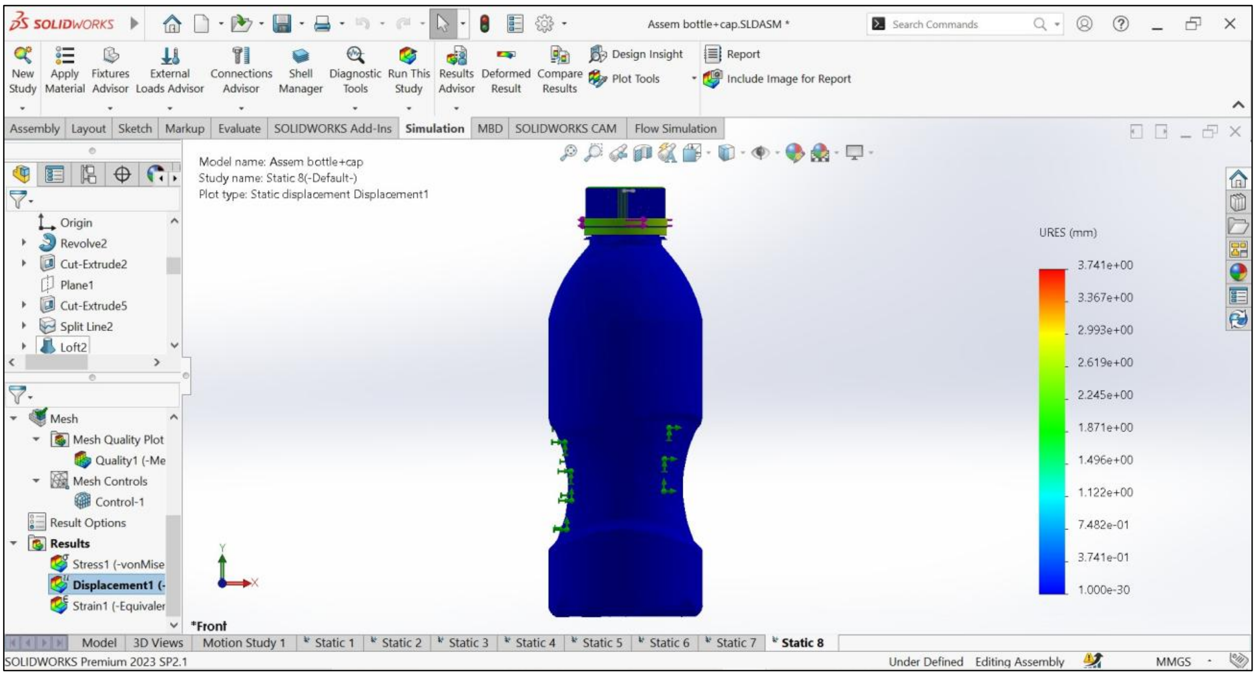

Fig. 11. Fixed support at the bottle body.

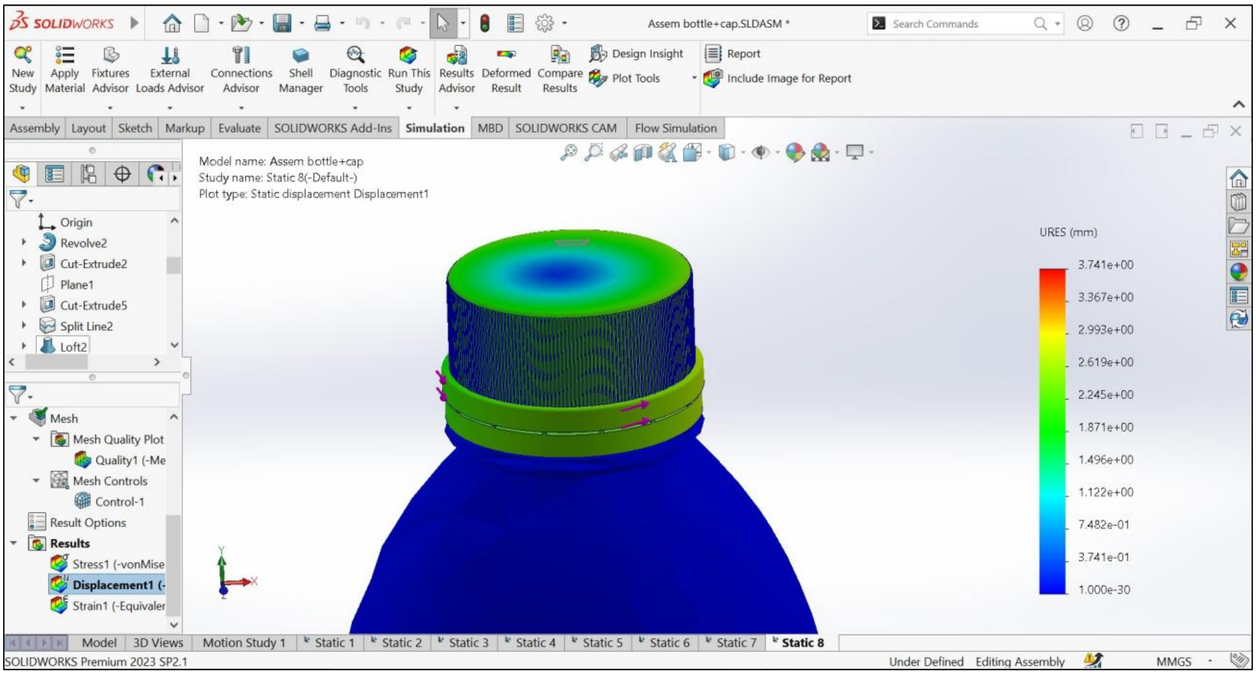

Fig. 12. Deformation of bottle cap under applied torque.

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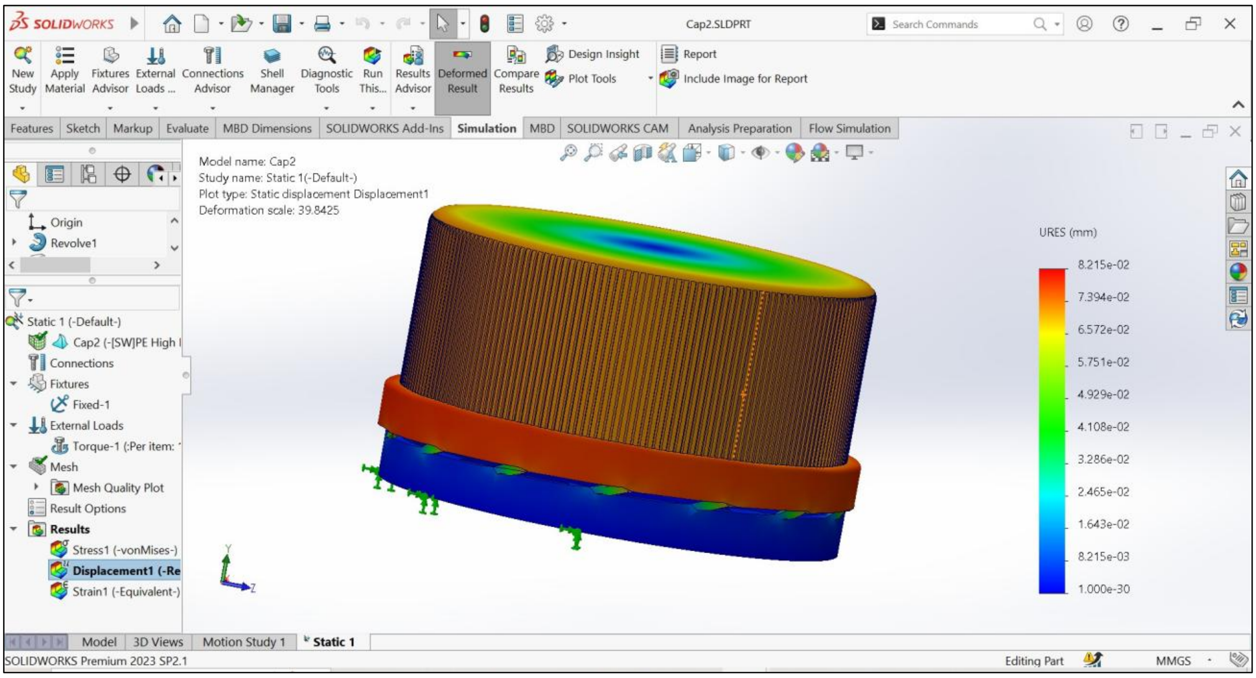

Fig. 13. Deformation of tamper-evident band connection under applied torque.

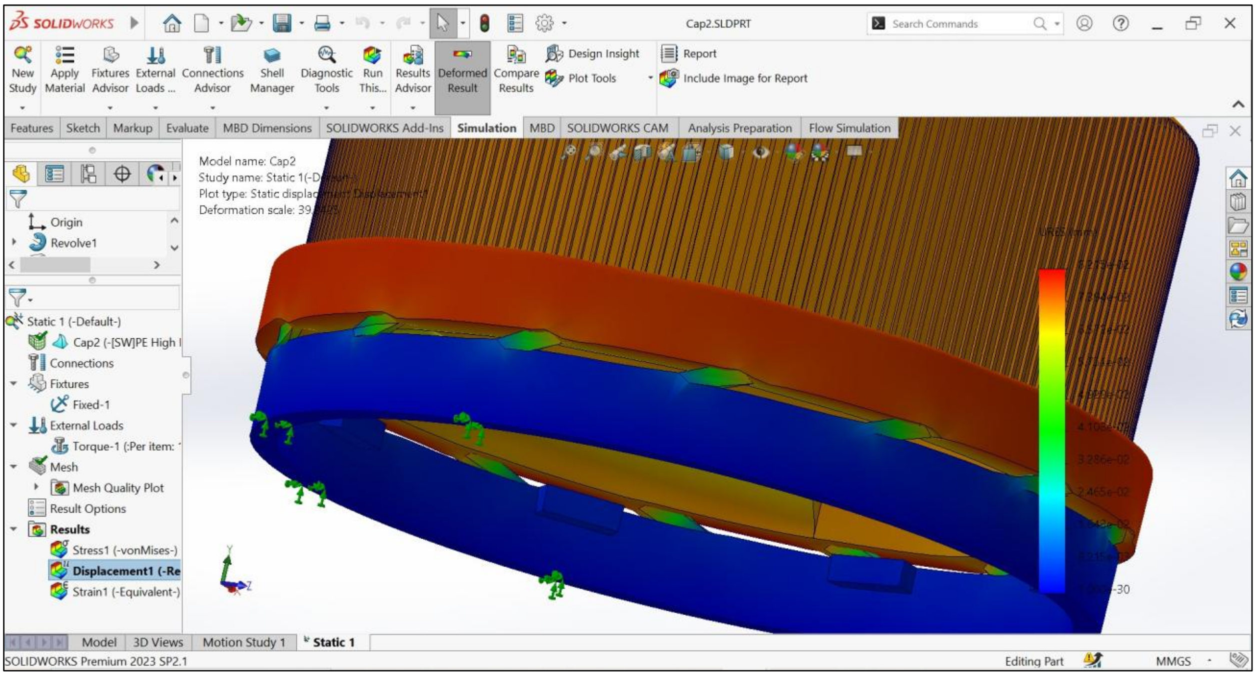

Fig. 14. Fixed support at the tamper-evident band base.

B. *Design Analysis*

Using Finite Element Analysis (FEA) helps optimize the bottle design by predicting and addressing potential issues before manufacturing, ensuring the bottle's strength and durability during use. The key components of the 330-ml bottle are the body-shaped platform base and the cap Key challenges include enabling one-handed cap opening while holding the bottle and ensuring the base remains stable and non-slip when placed on the floor. To address these challenges, recommendations for force-distribution simulations (Figs. 9-12) are proposed to optimize cap usability and base stability, enhancing the overall user experience and functionality. The design of the master model, however, is subjective, based on the design team's extensive experience in product design, development, and manufacturing. The body and cap were developed with this expertise in mind. With a minimalist design featuring a curved contour in the grip area, the bottle is optimized for easy handling, including opening and closing the cap and carrying the bottle while walking. A simple and clean design approach has been used to improve user convenience and functionality, ensuring an intuitive and effective product design.

Additionally, the design principles applied in this bottle can be adapted and contribute to the development of other packaging types. The focus on ergonomic design, ease of use, and stability can be extended to packaging for a variety of products, particularly those requiring convenient handling and transportation. The minimalist and functional design elements, such as a secure and user-friendly closure mechanism, can be integrated into different packaging solutions, ensuring better consumer experience across various industries.

C. Suggestion for bottle design platform

When manufacturers set out to design a new bottle, the first step is to identify and classify its key requirements:

- *Shape:* This includes considerations for the main body, which varies based on factors such as “size,” “ergonomic design,” “physical characteristics and aesthetic appeal,” and the “ease of opening and closing.”
- *Color:* This involves the “graphical design of the label” to enhance visual appeal.
- *Cap:* The cap design is based on the “bottle size,” the “bottle mouth size,” as well as the “ease of drinking” and “ease of opening and closing.”
- *Material Properties:* These include considerations for “strength,” “stiffness,” “durability,” and the capability to support a “long shelf life.”

Moreover, as detailed in Table 6, the outlines of key elements for a bottle design platform, developed specifically for the production ramp-up stage, are highly valuable for creating an accessible and efficient product design and development platform. These guidelines are intended to assist manufacturers in smoothly transitioning from prototype to full-scale production. By focusing on practical and efficient real-world application, the guidelines cover critical aspects such as user interface design, material selection, cost estimation, and compliance. This approach aims to streamline the production process, enhance collaboration, and ensure that designs meet both performance and sustainability standards.

Table 6. The key elements for creating an effective bottle design platform.

Key Element	Description
Customizable Frameworks	Provide a variety of frameworks for different bottle shapes, sizes, and materials.
3D Modeling Capabilities	Include advanced 3D modelling tools for real-time visualization and manipulation of designs.
Material Selection Tools	Provide options for selecting and experimenting with various materials, including sustainability considerations like recyclability.
Cost Estimation	Integrate a feature for estimating production costs based on design choices, materials, and manufacturing processes.
Prototyping and Testing	Include capabilities for creating prototypes and conducting virtual tests to evaluate design performance before physical production.
Collaboration Features	Enable users to collaborate and share designs with team members or stakeholders, facilitating feedback and iterative improvements.
Compliance and Standards	Ensure adherence to industry standards and regulations, with guidance on compliance for different markets and applications.
Integration with Manufacturing	Offer tools for seamless integration with manufacturing processes, including compatibility with CNC machines and injection molding.
Sustainability Insights	Provide information and tools for assessing the environmental impact of designs, including carbon footprint analysis and recommendations for eco-friendly practices.

7. Conclusion

This study integrates House of Quality (HoQ) and Linear Programming (LP) in the design of a 330-ml beverage bottle to address customer requirements and optimize manufacturing processes. By linking design elements to efficiency and cost considerations, the research reduces manufacturing costs and waste, enhancing sustainability. LP facilitates exploring alternative design options, balancing functionality and cost-effectiveness. Finite Element Analysis (FEA) is employed to predict and resolve potential issues, ensuring the bottle’s strength and durability. Key components include the body-shaped base and the cap, with challenges in one-handed use and base stability. Recommendations for force-distribution simulations aim to improve usability and stability. The design, reflecting extensive expertise, features a minimalist, curved contour for ease of handling. This approach aligns with market demands, enhances user experience, and supports sustainability goals.

8. Future Works

Future work in packaging design for the food industry will focus on integrating advanced machine learning algorithms to further optimize design processes and improve decision analysis in selecting prototyping methods. This will ensure even greater efficiency and cost-effectiveness in product development while addressing specific challenges faced by food packaging, such as shelf life, safety, sustainability, and consumer convenience. Key considerations for the future work include these following statements.

For "Reverse Engineering (RE)", RE will continue to play a critical role by allowing the creation of accurate 3D CAD models from existing packaging designs. This helps in modifying, improving, and troubleshooting packaging solutions for food products. By studying competitor designs and consumer feedback, RE can be applied to enhance functionality, material use, and visual appeal in food packaging.

For "Prototyping Techniques", prototyping is important for testing and refining food packaging designs quickly. Techniques such as injection molding, metal casting, and additive fabrication will be used to develop more sophisticated designs that meet the stringent requirements of the food industry, including durability, tamper-evidence, and ease of opening. These techniques allow for rapid iteration and scaling of new packaging solutions while maintaining high quality and compliance with food safety regulations.

For "Rapid Prototyping (RP)", advanced rapid prototyping techniques, such as *Fused Deposition Modeling (FDM)* and *Laminated Object Manufacturing (LOM)*, will be employed to fabricate prototypes layer by layer from 3D CAD models. These technologies will help reduce development time and cost, enabling designers to quickly test multiple design iterations. Decision analysis tools will be utilized to determine the most cost-effective RP process for different packaging materials, ensuring optimal functionality, environmental friendliness, and cost-efficiency.

These advancements will lead to the development of food packaging solutions that are not only aesthetically pleasing and functional but also capable of extending shelf life, improving food safety, and enhancing the overall consumer experience. Incorporating sustainable materials and eco-friendly designs will also align with the growing demand for environmentally responsible packaging options. Ultimately, the integration of these technologies will drive innovation in the food industry, resulting in packaging that meets both consumer expectations and regulatory standards.

In addition to designing bottles that reflect the preferences of target customers and fulfill their needs, it is equally important to ensure reliable transportation and logistics. These processes are vital for protecting the packaging and ensuring that the beverage is delivered safely, maintaining its original quality, freshness, and appearance throughout the supply chain [79-80].

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